Universidad
Carlos III de Madrid

TESIS DOCTORAL

Schemes for Multi-Hop Dissemination of Non-Safety Information in VANETs

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DEPARTAMENTO DE INGENIERÍA TELEMÁTICA

Leganés, Enero de 2016

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Firma del Tribunal Calificador:

Firma

Presidente:

Vocal:

Secretaria:

Calificación:

Leganés, 26 de Enero de 2016.

Ítaca

Si vas a emprender el viaje hacia Ítaca,
pide que tu camino sea largo,
rico en experiencias, en conocimiento.

A Lestrigones y a Cíclopes,
o al airado Poseidón nunca temas,
no hallarás tales seres en tu ruta
si alto es tu pensamiento y limpia
la emoción de tu espíritu y tu cuerpo.
A Lestrigones ni a Cíclopes,
ni a fiero Poseidón hallarás nunca,
si no los llevas dentro de tu alma,
si no es tu alma quien ante ti los pone.

Pide que tu camino sea largo.
Que numerosas sean las mañanas de verano
en que con placer, felizmente
arribes a bahías nunca vistas;
detente en los emporios de Fenicia
y adquiere hermosas mercancías,
madreperla y coral, ámbar y ébano,
perfumes deliciosos y diversos,
cuanto puedas invierte en voluptuosos y delicados perfumes;
visita muchas ciudades de Egipto
y con avidez aprende de sus sabios.

Ten siempre a Ítaca en la memoria.
Llegar allí es tu meta.
Mas no apresures el viaje.
Mejor que se extienda largos años;
y en tu vejez arribes a la isla
con cuanto hayas ganado en el camino,
sin esperar que Ítaca te enriquezca.
Ítaca te regaló un hermoso viaje.
Sin ella el camino no hubieras emprendido.
Mas ninguna otra cosa puede darte.

Aunque pobre la encuentres, no te engañará Ítaca.
Rico en saber y en vida, como has vuelto,
comprendes ya qué significan las Ítacas.

Constantin Cavafis

Acknowledgments

Tengo la suerte de haber encontrado a muchas personas que de algún modo u otro han estado a mi lado durante mi camino a Ítaca. A todas ellas quiero expresar mi agradecimiento en estas líneas.

En primer lugar, quiero dar las gracias a mi directora, Celeste, por haber puesto en mí su confianza desde hace tantos años y por haberme ofrecido siempre sin escatimar su tiempo y consejos. Ha sido un privilegio poder contar con las tres cosas. Extiendo el agradecimiento a Carlos, Florina, Andrés, Dani, Alberto y mis queridas amigas Patri y Ali. Más que un grupo os he sentido como una familia, donde he crecido tanto a nivel intelectual como personal.

También quiero dar las gracias a todos los compañeros del departamento de Ingeniería Telemática. Entre ellos, a Carlos Delgado, por darme la oportunidad de trabajar en el grupo GAST. Quiero mencionar especialmente a los profesores que me dieron clase y también a aquellos con los que he tenido la suerte de coincidir como docente: de todos he podido aprender valiosas lecciones. Agradezco con cariño a los doctorandos, investigadores y técnicos que actualmente están o en algún momento pasaron por el departamento, los estupendos ratos compartiendo vivencias dentro y fuera de las paredes de la universidad. Son muchos y no podría listarlos a todos, pero no quiero dejar de nombrar a Paloma, que ya se ha convertido en imprescindible para nuestro despacho, Sara Villanueva, Alberto Gordillo, Pedro, Derick, Luis de la Fuente, Isra, los "chicos Monoloc", José...

I would like to express my sincere gratitude to Prof. Schlichter and Wolfgang Wörndl from the Technische Universität München, for making my research visit possible. I must extend the acknowledgments to the whole group at the Chair of Applied Informatics / Cooperative Systems for integrating me in the group activities and for providing valuable insight into my research.

Finalmente, quiero dar las gracias a toda mi familia por su interés en mi tesis, las sesiones de psicólogo de andar por casa, las constantes muestras de apoyo y ánimo cuando tenía dificultades y su sincera alegría en los éxitos. Sin vosotros, dudo que hubiera podido terminar. En especial, a mis dos amores, Raúl y Diana, quiero agradeceros vuestra comprensión y ayuda en todo momento, sobre todo cuando he estado ausente por causa de esta tesis.

Resumen

La expresión inglesa Vehicular Ad Hoc Networks (VANETs) nombra a un tipo especial de Mobile Ad Hoc Network (MANET), cuyos nodos son vehículos y, ocasionalmente, dispositivos fijos con capacidad de comunicación. Lo que las hace especiales es el rango limitado de movimientos posibles para los nodos móviles (ya que sólo pueden viajar por las vías existentes) y su alta velocidad.

Las aplicaciones potenciales de este nuevo tipo de red son casi infinitas. La comunidad investigadora las ha clasificado típicamente en cuatro grupos: seguridad activa, apoyo a servicios públicos, asistencia a la conducción y negocios/entretenimiento. Los patrones de comunicación que precisan son variados, siendo la diseminación de información uno de ellos. Su objetivo es alcanzar a un grupo de vehículos en un área mayor que el de la cobertura alcanzada por un nodo, de modo que es necesaria una difusión multisalto. Esta puede tomar múltiples formas dependiendo del tipo de mensaje. Por ejemplo, una alarma provocada por un frenazo brusco requiere una diseminación rápida y confiable, mientras que un aviso de calle cortada es tolerante a retardos de hasta algunos segundos y si no alcanza a algún destinatario no supone un riesgo para la seguridad.

El trabajo contenido en esta tesis se enfoca en este último caso de uso. La meta es crear esquemas que permitan la diseminación multisalto de mensajes que no tienen requisitos fuertes en cuanto a retardo y entrega (típicamente, cualquier información no relacionada con la seguridad). Nuestros objetivos para esta solución son cuatro. Primero, queremos que sea útil en carretera así como en ciudad. Los movimientos de los vehículos y la existencia de obstáculos para la propagación de la señal son muy diferentes en ambos escenarios y por tanto necesitamos adaptarla a ambos. Segundo, queremos que no dependa de infraestructura. El coste de desplegar unidades fijas a lo largo de cada calle y carretera es alto, y puede llevar un largo tiempo hasta que haya cobertura global. Nuestra intención es que esta solución pueda ser usada en cualquier punto del proceso de despliegue. Además, debe evitar el problema conocido como “tormenta broadcast”, reduciendo en la medida de lo posible el número de duplicados generados. Por último, el esquema necesita hacer frente a particiones intermitentes de la red vehicular. Implementar un mecanismo de los llamados “store-carry-forward” (guardar-llevar-reenviar), que permita a un mensaje llegar a grupos desconectados de vehículos dentro de la zona de destino, aumenta el número de duplicados necesarios.

Para conseguir estos objetivos, primero estudiamos cómo esquemas típicos de diseminación sin apoyo de infraestructura, tomados del estado del arte en MANETs, más uno nuevo y específico, se pueden aplicar en VANETs. De acuerdo con los resultados en relación con una serie de métricas, hemos aprendido que el esquema basado en distancia es el que mejor cubre nuestros requisitos. Seleccionamos este para crear un esquema optimizado para los dos tipos de escenarios existentes: carretera (entorno interurbano) y ciudad (entorno urbano).

En cuanto a la adaptación al entorno interurbano, comenzamos optimizando el esquema de modo que su tasa de reenvío esté tan cerca del mínimo como sea posible, y analizando su retardo medio por salto en una red conectada (es decir, que hay al

menos una ruta posible entre dos nodos cualesquiera de la red). A continuación, estudiamos cómo añadir un mecanismo "store-carry-forward" específico para nuestra solución que, con cambios mínimos, consiga superar particiones de red breves. Validamos este añadido y el esquema completo bajo diferentes cargas de canal y en contraste con un conocido protocolo para este mismo tipo de tráfico, DV-CAST.

Nuestro trabajo en la versión para escenarios urbanos parte del supuesto de que necesitamos detectar intersecciones y reaccionar en consecuencia para poder extender la diseminación en nuevas direcciones y alcanzar tantos vehículos como sea posible. Creamos dos modificaciones del esquema basado en distancia, cada una en base a un método distinto para detectar cruces, y las probamos junto con el esquema básico. Este primer paso nos lleva a descubrir que no es necesaria dicha detección para poder conseguir buenos resultados. Después, de forma similar al proceso que seguimos para el escenario de carretera, trabajamos en optimizar el esquema y crear un mecanismo "store-carry-forward" apropiado. Seguimos el mismo razonamiento pero en esta ocasión consideramos tres opciones diferentes para las repetidas retransmisiones. Probamos cada versión del esquema concienzudamente con simulaciones, utilizando mapas reales de ciudades, y comparamos los resultados con los del equivalente urbano de DV-CAST, llamado UV-CAST.

Usamos simuladores validados como ns-2 y Veins para probar de forma realista las diferentes etapas de nuestro trabajo. Las prestaciones de los esquemas resultantes cumplen con nuestros requisitos en un alto grado, por lo que consideramos que hemos conseguido alcanzar nuestros objetivos. Además, el trabajo realizado hasta el momento abre la puerta a nuevas líneas de investigación que son, bien consecuencia natural, bien aplicación de nuestros logros.

Abstract

Vehicular Ad Hoc Networks (VANETs) are a special case of Mobile Ad Hoc Network (MANET), whose nodes are vehicles and occasional fixed devices with communication capabilities. What makes them special is the limited range of possible movements of the mobile nodes (they can only travel on the existing roads or rails) and their high speed.

The potential applications in this new type of network are almost endless. Researchers have typically classified them in four groups: active safety, public service support, improved driving and business/entertainment. The communication patterns that they require are varied, being information dissemination one of them. It is aimed at reaching a group of vehicles in an area that is larger than the reception range of a single node, so that a multi-hop broadcast is necessary. It can take multiple forms depending on the type of message. For example, a warning caused by a sudden brake requires a fast and reliable dissemination, whereas a blocked route announcement is tolerant to delays up to a few seconds and may miss some target without risking safety.

The work in this PhD thesis is focused on this last type of use. The objective is to create schemes that would allow for the multi-hop dissemination of messages that do not have hard delay and delivery requirements (typically, any non-safety information). Our goals for this solution are four. First, we want it to be useful in roadways as well as inside cities. Vehicles movements and the occurrence of obstacles to the signal propagation are very different in both scenarios and so we need to adapt it to both. Second, we want it to be independent of infrastructure. The cost of deploying fixed units along every road and street is high and it may take a long time until there is global coverage. Our intention is that this solution can be used regardlessly of the deployment point. In addition, it must avoid the broadcast storm problem by reducing as much as possible the number of generated duplicates. Lastly, the scheme needs to cope with intermittent partitions in the vehicular network. Implementing a store-carry-forward mechanism that allows a message reach disconnected groups of vehicles inside the destination area rises the number of necessary duplicates.

In order to achieve the aforementioned goals, we first study how typical infrastructure-less dissemination schemes from the state of the art in MANETs, plus a new specific one, apply to VANETs. According to their results in relation to a series of metrics, we learn that the distance-based scheme is the one that best meets our requirements. We select it to create an optimized scheme for the two existing scenarios—roadways and urban areas.

Regarding the adaptation for roadways, we begin by optimizing the scheme so that its forwarding ratio is as close to the minimum as possible, and analyzing its average per-hop delay in a connected network (i.e., there is at least one feasible route between any two nodes in the network). Next, we study how to add a custom store-carry-forward mechanism that, with minimal additions, manages to overcome short-lived network partitions. We validate the addition and the complete scheme under different channel loads and in contrast with a well-known protocol aimed at

the same type of traffic, DV-CAST.

Our work on the version for urban scenarios parts from the assumption that we need to detect junctions and react accordingly in order to spread the dissemination in new directions and reach as many vehicles as possible. We create two different modifications of the basic distance-based scheme, each using a different method to detect intersections, and test them along with the basic one. This first step leads us to discovering that it is not necessary to detect intersections in order to achieve good results. Then, similarly to the process for the roadway scenario, we work on optimizing the scheme and creating a suitable store-carry-forward mechanism. We follow the same reasoning but this time we consider three different options for subsequent retransmissions. We test each version of the scheme throughly via simulations using real city maps and compare the results to those of the urban counterpart of DV-CAST, named UV-CAST.

We use validated simulators as ns-2 and the Veins framework for testing realistically the different stages of our work. The performance of the resulting schemes meet our requirements to a high degree and so we consider that we have fulfilled our goals. In addition, the work done so far opens the door to new lines of research that are either the natural consequence or an application of our achievements.

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Chapter 1

Introduction

1.1 Motivation

Since the early 90s, the research community has been working on ways to provide vehicles with the ability to communicate. The first idea was to install a device that would negotiate payments with toll booths wirelessly. This opened a new field and, the following decade, the interest had shifted to creating platoons of vehicles and improving the safety. The perspective of avoiding collisions and saving lives motivated the USA government to orchestrate a series of actions in order to standardize and deploy a short-range communications system for vehicles. Other powers like the European Union (EU) and Japan have followed and developed their own standards over the last decade.

This was the origin of Vehicular Ad Hoc Networks (VANETs), which are considered a special case of Mobile Ad Hoc Network (MANET). The latter are composed of mobile and independent nodes that communicate without the need of a central management base. Those nodes are typically assumed to be a human being holding a communication device, as a smartphone. VANETs, for their part, are mainly composed of (motor) vehicles. Fixed units are also considered, either as central management entities (like a certificate server), access points to other networks (as the Internet) or service support units (like traffic lights or a fixed service advertiser). Vehicles travel through streets, roadways or rails and are able to send messages to others and to those fixed units. This confers a series of characteristics on VANETs that set them apart:

- Vehicles move at higher speeds than those considered for traditional MANETs.
- Their trajectories are more deterministic, as their movements are limited by roads and driving rules.

We have chosen this new type of ad hoc network as the framework of our work. Its potential applications are numerous and varied. Given the interest, during the first years of standards development several works presented relatively similar taxonomies on the types of application and the communication patterns. For example, the authors of [Willke et al., 2009] identified four classes of applications according to their communication paradigm:

1. *General information services* are not related to safety and they can tolerate delays or even loses. The exchanged messages are information queries (like weather reports) or broadcasts to a group of vehicles (advertising, for example).

2. *Vehicle safety information services*, contrary to the first group, have hard real-time requirements in order to guarantee safety. The type of message would be safety warnings to alert about potential dangers.

3. *Individual motion control* refers to those applications that will assist drivers or help regulate traffic. They need local broadcasts to announce the presence and other information to surrounding peers.

4. *Group motion control* consists on creating platoons of vehicles that share a destination, freeing the user from driving. It also needs frequent state broadcasts among the involved vehicles.

We can find a similar classification in [Schoch et al., 2008], where application types are divided into the following four groups:

1. *Active safety* applications, that prevent dangerous situations. This class would match type 1 of the taxonomy above.

2. *Public service* support, as tools for taking actions in case of an accident (calling the emergency services, alerting coming vehicles, etc).

3. *Improved driving* to assist drivers, that matches type 3 of the other classification.

4. *Business/entertainment* for any other use, just like type 1 of said classification.

According to this taxonomy and to the specific network characteristics of VANETs, these authors distinguish five different communication patterns that may take place in them:

Beaconing: Its purpose is to constantly update the status information of the sending vehicle to its neighbors. Hence, messages are periodically broadcast to one-hop vehicles and typically never forwarded. The communication is unidirectional, from every node to all the neighbors in reception range.

Geobroadcast: The sender wants to immediately inform all the vehicles in a larger area about a sudden event. For example, a vehicle that suddenly brakes needs to inform coming vehicles about it. Depending on the message, it may be repeated from time to time and have more relaxed time and delivery requirements, like in a case of work zone warning. The forwarding scheme may be optimized to reduce overhead in cases of high node density.

Unicast routing: This would be the case for unicast data transport. The communication may be uni- or bidirectional. It may consist of a single hop or a route over multiple hops towards a single vehicle or a destination region.

Advanced information dissemination: The goal is to provide information among vehicles in a given area during a certain time, bridging network partitions. In this case, a wide coverage and time stability for the dissemination are more important than low latency. Thus, this type of communication usually applies store-carry-forward mechanisms, in which a relay node awaits new neighbors before forwarding the message one or more times.

Information aggregation: As opposed to the other communication patterns, in which the message is not modified at each hop, vehicles process and merge the received data with their own information before putting it again in the medium. The central component is a knowledge base that is updated with every received message and shared at every new transmission. The objective of the communication is that each node's base gets to represent accurately the global knowledge of all the vehicles in the network.

We focus on creating a dissemination scheme that fits both the relaxed geobroadcast and the advanced information dissemination patterns: it should minimize the overhead in dense traffic situations (large connected network) and reach as many vehicles as possible in sparse traffic (disconnected small networks). Such a scheme could be useful for public service, improved driving and, especially, business/entertainment applications. As an example, it could be used for disseminating warnings about a blocked road or announcements of scenery overlooks in the route or sales in the downtown area.

According to renowned researchers [Viriyasitavat et al., 2009], we must first distinguish between two types of target scenario, due to their differences in connectivity patterns: roadways and urban areas. In [Viriyasitavat et al., 2011], the same authors present a list of challenges that are present in the latter but not in roadways. Urban scenarios are especially sensitive to broadcast storms because of the high density of vehicles in downtown areas. On the other hand, low traffic densities, as well as the disruptions in propagation caused by buildings and other obstacles, accentuate the problem of network partitioning.

Our work is contemporary to the standardization efforts that we mentioned at the beginning. In the American standard, DSRC, the dissemination is transferred to IPv6 and its mobility extensions. On the other hand, the European standard, ITS, describes three possible approaches that were standardized just recently (in July 2014). This has supposed a void for the types of application mentioned above during a decade, and so researchers have been proposing solutions since 2005. The research community has produced a wide variety of schemes, from general solutions, better suited and mainly tested on roadway scenarios, to specific schemes for cities. To the best of our knowledge, there are only two well-known solutions that meet our requirements of low redundancy, and resiliency to network partitions—DV-CAST [Tonguz et al., 2010] and UV-CAST [Viriyasitavat et al., 2011]. They are intended for roadways and cities, respectively. Their operation is based on three components: neighbor detection, a broadcast suppression mechanism and a store-carry-forward mechanism. The neighbor detection is achieved by means of periodic status updates that every vehicle emits. With the location information contained in them, each one can estimate its local topology and determine if it is in a well-connected or disconnected network. In the former case, it will apply the broadcast suppression mechanism. The goal of such a mechanism is to selectively inhibit forwarders to avoid a broadcast storm. In the latter case, the store-carry-forward mechanism helps the dissemination cover the area of interest despite the poor connectivity.

At the moment of contemplating our goals and requisites, we decided that it was interesting to avoid the use of status beacons. First, we considered that defining our own additional beacons would mean making a poor use of the available bandwidth. Not relying on the status messages that were being defined for the developing standards, freed us from adjusting to their message format and other evolving specifications. And most importantly, we could contribute to the state of the art by checking the differences in performance between this new approach and the mentioned protocols, DV-CAST and UV-CAST.

1.2 Objectives and Requisites

Based on the ideas presented above, we set the following list of objectives:

- **Study the state of the art on multi-hop dissemination and traffic mobility in VANETs.** We need to gain a comprehensive knowledge of the literature on the subject of dissemination, in order to identify key features and lacks of the dissemination schemes presented so far. In addition, we need to learn the main proposed models for traffic mobility in the different target scenarios.

- **Design solutions for multi-hop dissemination for roadways as well as for city grids.** Our intention is to create a holistic set of schemes that vehicles can apply no matter their location. The requisites we set for them are the following:

  1. *Avoid support from fixed devices.* The first models of connected cars have come out on the market very recently and, even so, we cannot assume every road and every street of the globe will be equipped with communication devices. In order to make this solution applicable since day one, we need to be independent from fixed infrastructure.
  2. *Prioritize efficiency.* We focus on non-safety applications that may offer any kind of delay-tolerant service. Given that their function is not a matter of life or death, they may occasionally miss a target. Besides this, the shared bandwidth is a limited resource. It may become scarce inside cities and in traffic jams, where many vehicles will be emitting

status updates and trying to access different services. So, we will try to minimize the impact in the bandwidth usage in well-connected networks by reducing the redundancy.

3. *Provide a mechanism for bridging network partitions.* When the traffic is sparse, large gaps between connected groups of vehicles appear, partitioning the vehicular network. We want to let the message travel through these gaps by creating a store-carry-forward mechanism that is adapted to our solution.

- **Assess the performance of the proposed solutions.** By evaluating our designs, we will be able to pinpoint their benefits and limitations. It is specially interesting to put our schemes in contrast to well-known solutions, in order to understand our contribution to the state of the art. This goal will let us draw our conclusions and also discover lines of further work.

1.3 Work Plan

We summarize the main tasks that were necessary to accomplish the objectives.

- Gather and understand the bibliography related to multi-hop dissemination in VANETs in order to identify the main advances and the necessities not covered to the date.

- Evaluate different basic forwarding schemes in a vehicular environment to find the one that optimizes the efficiency.

- Design an algorithm that covers the area of interest with the minimum number of retransmissions in a roadway setting.

- Design a mechanism that will help said algorithm overcome short disconnections due to gaps between groups of connected vehicles.

- Study how to make the basic scheme for efficient forwarding also suitable for the more complex scenario of urban areas.

- As with the version for roadways, design a mechanism that will alleviate the problem of network partitioning in the urban environment.

- Run validation and evaluation tests in order to assess the performance of the proposed schemes at each stage.

- Compare the performance with that of well known solutions.

- Draw the main conclusions from the research and identify new lines of work to follow.

- Disseminate the different outcomes of the research via publications in scientific conferences and magazines.

- Write the dissertation document.

1.4 History

When I started this thesis in 2009, the vehicular technology was very young and the first standards for future development were being released. Understandably, the general interest was put in applications that would enhance the safety. Hence, the typical motivation for a multi-hop broadcast was the rapid notification of a dangerous event (such as a car crash) to following vehicles in a roadway, in order to avoid successive collisions. We set our focus on the dissemination of non-safety information because this topic was less explored at the moment. The intrinsic necessities of this type of application led us to work on an efficient use of the shared bandwidth instead of on speed or reliability.

After the initial exploration of the literature, we started by studying different basic algorithms that were common in MANETs. We wanted to evaluate their performance in a simple VANET in order to set a good basis. So, we chose a popular network simulator with support for vehicular characterization (ns-2[1]) and a straight roadway scenario with vehicles moving in both directions. We published our results in the article "Bandwidth Efficient Broadcasting in VANETs" [Garcia-Lozano et al., 2012a].

Having selected a strategy, we started our work on designing and testing an algorithm for roadways. This study was published in our paper "An Efficient, Eco-Friendly Approach for Push-Advertising of Services in VANETs" [Garcia-Lozano et al., 2012b]. We discovered that disseminations in settings with a low traffic density are prone to suffer from short disconnections that worsened the overall performance. This led us to promptly work on a mechanism that would solve this problem. We presented the enhanced broadcast scheme in our article "A Bandwidth-Efficient Service for Local Information Dissemination in Sparse to Dense Roadways" [Garcia-Lozano et al., 2013a].

At the end of 2012 I had the opportunity to spend three months working within the Chair of Applied Informatics and Cooperative Systems in the Department of Informatics of the Technische Universitaet Muenchen in Germany. There, I was able to design an application that was supported by our dissemination scheme. We developed a traffic information system (TIS) in which vehicles collaborate to inform about the traffic conditions to a requester while minimizing the security risks. We presented the solution in the article "A New Traffic Information Service for Smart Consumer Devices" [Garcia-Lozano et al., 2014b].

Once the scheme for roadways was complete, we began to analyze the more complex scenario of urban areas. This coincided with a wave of interest in the same type of environment from the research community that still remains. Better suited simulators for urban vehicular networks caused our change to Veins for this stage of the process. We evaluated different options to tackle the problems in urban areas and published our conclusions in the article "Bandwidth-

[1] `http://www.isi.edu/nsnam/ns/`

Efficient Techniques for Information Dissemination in Urban Vehicular Networks" [Garcia-Lozano et al., 2014a]. A more in-depth study of the same options is in the article "Adapting a Bandwidth-Efficient Information Dissemination Scheme for Urban VANETs" [Garcia-Lozano et al., 2015].

The realization of most of this thesis was in the context of the project TEC2010-20572-C02-01 "CONSEQUENCE", founded by the Spanish Ministry of Science and Innovation. Our partners were the Telematic Services group from the Unversitat Politecnica de Catalunya. This enriched the process and one of the outcomes is a collaboration to create a system for accident prevention in roadways. It was published in the article "A distributed, bandwidth-efficient accident prevention system for interurban VANETs" [Garcia-Lozano et al., 2013b].

1.5 Structure of this Document

In this chapter we have established the motivation and objectives of this dissertation, as well as more practical details. The rest of the document is structured as follows.

Chapter 2 presents the state of the art on the subject of multi-hop broadcast in vehicular networks. First, we give an overview of the standards from USA and Europe and their solutions for disseminating information. Then, we present a varied selection of works from the research community within three different scopes: MANET networks, roadways and cities.

Chapter 3 contains the main tools we have used for designing and evaluating the different stages of our work, from mobility models to simulators and metrics.

We start describing our actual work in Chapter 4. We part from an usual classification of dissemination schemes from MANETs and apply each type to a simple VANET scenario. We select the scheme that has the best performance in redundancy, in order to build our solutions upon it.

In Chapter 5 we describe the reasoned design of the complete scheme for interurban scenarios. This includes the adaptation of the basic scheme to roadway scenarios and the addition of a store-carry-forward mechanism to improve the performance in sparse traffic situations. We include extensive evaluations, including a comparative with a popular solution from the state of the art and a series of proofs of concept.

Chapter 6 is dedicated to the adaptation of the scheme to urban scenarios. As in the previous chapter, we first optimize the basic scheme for its operation in urban areas and then create a custom store-carry-forward mechanism. The evaluations also include a comparative with a well-known urban dissemination scheme.

Finally, in Chapter 7, we summarize the main conclusions we have reached during the realization of this dissertation. Furthermore, we reflect on the lines of work that follow as a consequence of this thesis.

Chapter 2

State of the Art

One of the objectives listed in the previous chapter was to gain a comprehensive understanding of the state of the art in the subjects of information dissemination and traffic mobility in VANETs. We cover the former in this chapter, and leave the topic of traffic models for the next, along with other practical issues. We divide the reviewed literature into two main lines. The first one is about the standardization efforts and, specifically, their approach to multi-hop dissemination. The current standards have been under development until very recently, but at the same time, the research community has been proposing protocols for this task over the whole last decade. We have selected a few characteristic examples that implement different techniques and present them in the second part of this chapter.

2.1 Standardization of Vehicular Communications

The wish to integrate communication capabilities into vehicles has been present since the early 90s [Kawashima, 1990]. They are expected to be the key to drastically reducing accidents and making trips safer. They can also help in a better traffic management and trip efficiency. Since then, several organizations and governments around the world have been working towards defining and standardizing the use of wireless communications among vehicles (V2V) and between vehicles and infrastructure (V2I). The resulting solutions are not global, though. Each country is competent to establish the operating frequency band in which vehicular communications will take place. Public infrastructure and an important part of research funding is paid by governments, while private corporations and non-profit organizations put an effort on research that makes sense locally. The two main sets of standards for vehicular communications are the Dedicated Short-Range Communications (DSRC) [DOT HS 810 591, 2006] by the Institute of Electrical and Electronics Engineers (IEEE) from the USA, and the Intelligent Transportation Systems (ITS)[1] by the European Telecommunications Standards Institute (ETSI). They both have

[1] http://www.etsi.org/technologies-clusters/technologies/intelligent-transport

released most of their standards since 2010 and the working groups are still very active. Thankfully, the two architectures are designed so that their differences are not impossible to overcome and vehicles from both sides could operate in the other region.

2.1.1 DSRC

The efforts towards creating connected vehicles date back to the 1990s, when Radio Frequency IDentification (RFID) transponders were applied to toll collection in the USA. The same suppliers of toll collection electronics envisioned that the 915 MHz band could also support road safety applications. In the same decade, several studies agreed that short-range communications (less than 100 m) would be enough for most vehicular safety and collision avoidance applications. Later on, the DSRC community changed to the IEEE 802.11 technology over the 5.9 GHz band, to take advantage of its already developed infrastructure and ad-hoc modes. All this resulted in the IEEE 802.11p and IEEE 1609.x standards, that form the DSRC suite of standards [Morgan, 2010].

Architecture

The Wireless Access in Vehicular Environments (WAVE) architecture is detailed in [IEEE 1609.0, 2013]. The layers contained in this standard are depicted in Figure 2.1 with solid lines. Layers in dotted lines complete the overall architecture for DSRC.

The standards for the PHY and MAC levels are IEEE 802.11p together with IEEE 1609.4. The 802.11p amendment deviates only slightly from the main 802.11 standard, in order to encourage manufacturers to add support to 802.11p to their chips [Kenney, 2011]. 802.11p is now integrated into the 2012 standard revision [IEEE 802.11, 2012]. The standard [IEEE 1609.4, 2011] introduces the use of several channels and a mechanism for channel switching. The LLC sublayer is based on [IEEE 802.2, 1998].

The network and transport layers are divided into two different stacks, depending on the application above. Safety and other local applications use the WAVE Short Message Protocol (WSMP). This protocol, that covers both layers, is defined in [IEEE 1609.3, 2010]. It is based on a new type of message, the WAVE Short Message (WSM), that is specific for local, ad-hoc communications. Other applications use the TCP/IP stack. In such a case, UDP is advised over TCP, and only IPv6 can be used.

On the management plane, we can distinguish between security and management *per se*. The WAVE Security Service is defined in standard [IEEE 1609.2, 2013] and provides access points to every layer in the architecture's data plane. The management entities, on the other hand, are specific to each layer in the data plane and defined in the corresponding standard.

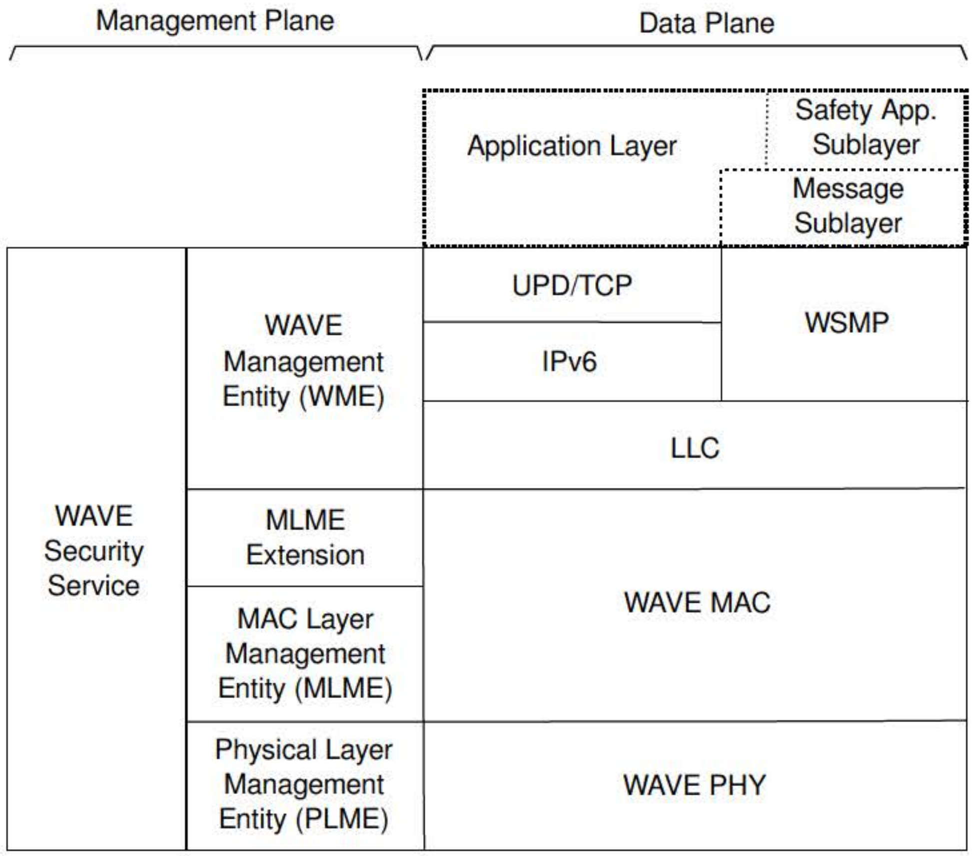


Figure 2.1: DSRC architecture.

Multi-hop Dissemination

As mentioned just above, the networking and transport layers are divided into two stacks–WSMP for safety applications and UDP/IPv6 for the rest.

DSRC understands safety applications with a very local scope (a few hundred meters at most). They are based on short status messages (WSM) that are broadcasted to one-hop neighbors. Hence, WSMP does not include any multi-hop dissemination scheme. Instead, any information that needs to be relayed beyond that, goes into an IPv6 packet. The goal behind this is to avoid overlaps in functionality between the different protocols in the DSRC architecture.

2.1.2 ITS

The ETSI and the Comité Européen de Normalisation (CEN) are the standardization organizations in charge of developing a minimum and consistent set of standards for the European Union. Their technical committees, ETSI TC ITS and CEN TC 278, are working since 2010 in close liaison with ISO TC 204, and they published Release 1 for early deployment of Collaborative Intelligent Transport Systems (C-ITS) in 2013.

The standards consider the ITS sub-system (ITS-S) as the center piece. It may be a personal device (as a wearable one), a vehicle, a roadside unit or a central system (like a traffic management center). They may work as a simple host, a gateway (connecting two different protocol stacks), a router (connecting two different ITS-S systems at layer 3) or a border router (connecting an ITS-S to a different entity at layer 3), depending on the network functions it is capable to assume.

Architecture

The general architecture for a ITS-S is specified in [ETSI EN 302 665, 2010] and shown in Figure 2.2. The access layer focuses mainly on communication over G5, that refers to the 5GHz band allocated for ITS. It is a variant of WAVE, adapted to the European requisites. Other access technologies, like cellular, are also considered.

The Networking and Transport layer considers two different protocol stacks. First, the Basic Transport Protocol (BTP) over GeoNetworking are aimed at totally ad hoc communications over G5. Messages are sent towards topological destinations (geo-addressing) rather than logical addresses. The other protocol stack for this layer is the traditional TCP or UDP over IPv6, including mobility extensions for IPv6 and other mobility-focused transport protocols like Stream Control Transmission Protocol (SCTP). Obviously, peers are identified by IPv6 addresses. This is used mainly for information that is sent out of the ad hoc network at some point. Also, an application may require Internet protocols but it is for use inside a geo-addressed network over G5. GN6 is an adaptation sub-layer that carries IPv6 packets over GeoNetworking.

The Facilities layer provide a range of high level functionalities, as selection of the addressing mode, session management, data presentation, location, time and

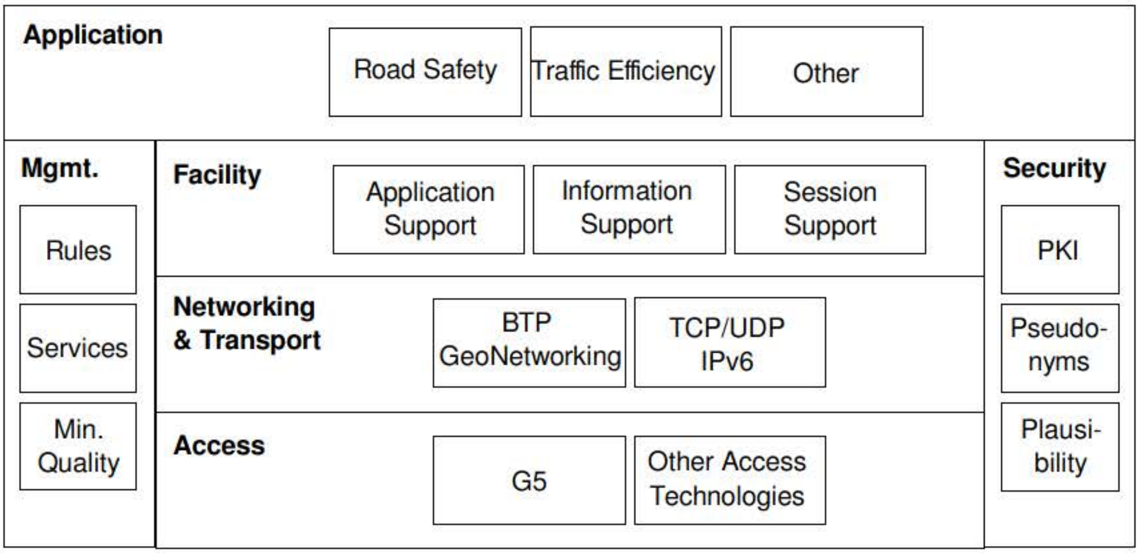


Figure 2.2: ITS architecture.

other data provision, application support and others. Finally, the Application layer contains all the applications that provide usefulness to vehicular networks. For example, the generation of periodic—Cooperative Awareness Message (CAM)—or event-driven—Decentralized Environmental Notification Message (DENM)—status messages for safety, services, or traffic information systems.

There are two vertical entities that affect all horizontal layers: Management and Security. The Management entity relies on a general Management Information Base (MIB) and supports different utilities: general congestion control, service advertisement, application mapping or local node map (neighbors information), to name a few. The Security entity makes use of a Security Information Base (SIB) and takes care of all the different aspects of security at every level of the protocol stack—confidentiality, integrity, availability, authentication, non-repudiation and privacy. It will need support from central systems depending on the security requirement.

Multi-hop Dissemination

GeoNetworking is the routing protocol intended for ad hoc communications over G5. It is defined in the ETSI EN 302 636-4 standard series. The different packet handling modes are GeoUnicast, GeoBroadcast, GeoAnycast, Single-Hop Broadcast, and Topologically-Scoped Broadcast. We are interested in GeoBroadcast, that uses geo-addressing for a multi-hop dissemination. It is used for DENM messages (event-triggered updates) among other applications. The forwarding algorithms can be found in subpart 4-1.

GeoBroadcast packets are disseminated inside a destination area, DAp, as defined in the header. It includes coordinates of the area center (LAT and $LONG$), two distances from the area center (a and b) and an angle. The header sub-type (HST) value indicates whether they refer to a circular (0), rectangular (1) or ellipsoidal (2) area, so that these variables are correctly interpreted.

The packet also includes the next hop. Depending on the forwarding algorithm, relays (called GeoAdhoc routers) may elect themselves or may be pre-chosen by the previous one. In this standard, when a device (source or not) applies a function to determine the next relay, it is said to be calculating the address of the next hop. It may get a result or not. In the latter case, it stores the packet for later.

The last relevant header field is the Hop Limit (HL), that acts as a Time To Live (TTL). Every GeoAdhoc router decrements its value before forwarding. If the new value is 0, the packet is dropped right away.

Packets may originate outside of the DAp, so the different algorithms distinguish between two approaches to forwarding: towards and inside it. The source and any GeoAdhoc router determine their forwarding mode by comparing the DAp in the header with their own location, referred to as $F(x, y)$, as in Equation 2.1.

$$\text{I am ...} \begin{cases} \text{in the center of DAp} & \text{if } F(x,y) = 1 \\ \text{inside DAp} & \text{if } F(x,y) > 0 \\ \text{on the edge of DAp} & \text{if } F(x,y) = 0 \\ \text{outside DAp} & \text{if } F(x,y) < 0 \end{cases} \tag{2.1}$$

Simple GeoBroadcast forwarding algorithm with line forwarding If the GeoAdhoc router is outside the DAp ($F(x, y) < 0$), it applies the Greedy Forwarding algorithm (GF) to obtain a destination address (i.e. next hop). This part of the mechanism is called line forwarding. Otherwise, it passes the message to the upper level (as it is a target) and rebroadcasts the packet.

GF returns a destination address for a packet that is being forwarded towards the DAp. In other words, it is used to select the next hop in the dissemination. It parts from the DAp center coordinates, (x, y), and applies the Most Forward within Radius (MFR) policy: the neighbor that is closest to the DAp is the next hop. It is possible that the one who is closest, is the current relay. In that case, there is no new destination to return.

The Technical Specification from 2011 [ETSI TS 102 636-4-1, 2011] added two Advanced GeoBroadcast forwarding algorithms that improved the Simple GeoBroadcast scheme. As stated there, they were *"experimental and provided for informative purpose"*. They have been perfected and are presented in the Standard as the Contention-based forwarding (CBF) algorithm for GeoBroadcast, and the Advanced GeoBroadcast forwarding algorithm.

Contention-based forwarding algorithm for GeoBroadcast Similarly to the CBF algorithm for GeoUnicast, it lets the nodes inside the DAp contend to be the next hop instead of choosing it at the sender. Nodes that are outside the DAp apply the line forwarding technique described above, by selecting the next relay with GF. In the contention area, a receiver that is not able to determine the location of the sender will wait a maximum delay, TO_MAX. Otherwise, it computes a timeout

(TO) with Equation 2.2:

$$TO = \begin{cases} TO\_MAX - \dfrac{(TO\_MAX - TO\_MIN) \times DIST}{DIST\_MAX} & DIST \leq DIST\_MAX \\ TO\_MIN & DIST > DIST\_MAX \end{cases} \tag{2.2}$$

$DIST$ is the distance to the previous hop and $DIST\_MAX$ is the theoretical maximum coverage radius. When $DIST$ is close to $DIST\_MAX$, the wait approaches the minimum delay, TO_MIN. When $DIST$ tends to zero, TO gets close to the maximum wait, TO_MAX. This way, the node that provides the greatest gain in coverage is the first to forward. The nodes that are still waiting when this happens, will cancel the retransmission after receiving the duplicate.

Advanced forwarding algorithm for GeoBroadcast It is intended for a more reliable broadcast inside the DAp. It combines source routing for fast delivery, CBF for reliability, and a counter-based broadcast suppression mechanism and a sectoral one for efficiency. For dissemination towards the DAp, it applies GF like the other two algorithms. This mechanism is carried on inside the DAp: a GeoAdhoc router that receives a packet addressed to itself will select the next hop via GF and forward immediately. The algorithm addresses the case in which the selected next hop does not receive the packet, and so the dissemination fails. This could happen if the packet is lost because of congestion, or because the node moves away from the sender. So, every other node that receives a packet participates in a CBF and forwards the packet to the broadcast address. In addition, every vehicle associates a counter to every packet. A GF sender will initiate the counter to 1 and a timeout to TO_MAX. CBF contending nodes start the counter at 0 and their timers to the corresponding delay. Every time a duplicate arrives, the counter is incremented. The moment it reaches a maximum value, the packet is discarded and the timer canceled. This reduces the number of retransmissions inside the area. To reduce them even more, receivers apply the sectoral broadcast suppression scheme presented in MHVB [Osafune et al., 2006] (summarized later in Sect. 2.2.2) when a duplicate arrives. It consists on passing the locations of the new forwarder, F, the sender, S, and the given GeoAdhoc router, R, to function G in Equation 2.3:

$$G = \begin{cases} +1 & (DIST\_R < DIST\_F)\&(DIST\_F < DIST\_MAX) \\ & \&(\angle F\,S\,R \leq ANGLE\_TH \\ -1 & \text{otherwise} \end{cases} \tag{2.3}$$

In this equation, $DIST\_R$ is the distance from the sender, S, to the GeoAdhoc router, R, while $DIST\_F$ is the distance to the new forwarder, F. $\angle F\,S\,R$ is the angle formed by these two distances and $ANGLE\_TH$ is a threshold for its value. Finally, $DIST\_MAX$, as above, is the theoretical maximum coverage radius. This means that, when $G > 0$, node R is inside the sector covered by the new forwarder, F, and must abort the retransmission because it will not cover any additional area.

And vice versa, if $G < 0$, R can increment the counter and, if appropriate, keep waiting for its timeout.

2.1.3 Conclusions on Standardization

We have briefly summarized the standardization efforts by American and European organizations. They have been intense during the last few years. The results: two series of standards being slowly released since 2009 and the first connected cars appearing in Europe in 2015.

Good news is that both standard sets are aware of each other and not completely incompatible, as they share almost the same PHY-MAC basis. On a higher level, and regarding multi-hop dissemination, they take very different approaches.

American DSRC considers that multi-hop routes should be tackled by IPv6. This cannot be done straight away, as IPv6 is not adapted to geographic routing. Some researchers have worked on this idea [Baldessari et al., 2007, Tsukada et al., 2010].

European ITS, on the other hand, includes three multi-hop broadcast schemes in the GeoNetworking definition. These have been provisional until recently, and researchers keep working on them [Kuhlmorgen et al., 2015].

With all the potential applications that can take advantage of a multi-hop broadcast, it is no wonder many authors have put their efforts on filling this void, creating fast or efficient solutions in the last decade. We list some of the best known of the aforementioned solutions in the next section. They are the base of our work, given the specif period in which we have carried it out.

2.2 Dissemination in VANETs

As we explained in Section 1.1, VANETs are a specific type of MANET. The interest in multi-hop broadcasts in MANETs caused abundant literature on the subject. We offer a small summary of the general techniques in Section 2.2.1. Some have been adapted with success to roadway scenarios. The main solutions for them can be found in Section 2.2.2. In urban settings, on the other hand, they are often combined or completely replaced by new approaches that deal with the abundant physical obstacles to signal waves that are present in them. A selection of relevant works in this area is in Section 2.2.3.

2.2.1 Dissemination in MANETs

The characteristics of a MANET are:

- Its nodes are mobile.
- They form a totally or partially connected network.
- The communications are one-to-one or one-two-many without the aid of a central manager.

In addition, there may or may not be physical obstacles in the network area, and no assumption is made about this subject.

Regarding a multi-hop broadcast, the authors of [Ni et al., 1999] offer a basic description. First, it is spontaneous (there is no previous synchronization) and it is not necessarily reliable. It is essential that nodes can detect duplicate messages in order to prevent the endless flooding of a message. A way to do this is by using the tuple <sourceID, sequence number>, as in the routing protocols for MANETs, Dynamic Source Routing (DSR) [Johnson et al., 2007] and Ad hoc On-Demand Distance Vector Routing (AODV) [Perkins et al., 2003]. Also, forwarded messages are not supposed to be identical to the original. Relay nodes may include or change information (as its ID or location).

The most straightforward way to disseminate information in a MANET is by doing a simple flooding—each node forwards every message that it receives for the first time. In a connected network with n nodes, a dissemination will cause $n-1$ retransmissions. However, as pointed out in the same work, this causes a broadcast storm problem in a CSMA/CA network. The authors give an analysis of the problem:

- Redundant retransmissions. The maximum additional coverage when forwarding after hearing a message for the first time is of just 61%. The average value is 41% and after the second duplicate, this expectation is lowered to 10%.
- High contention. When four or more nodes receive a message, the probability of them all taking part in a contention is close to 70%. If they are six or more, it raises to 80%.
- High probability of collisions, especially if the network was silent long enough for all the nodes to finish their CSMA/CA's backoff procedures. Then, they all will try to retransmit after the DIFS period at the same time.

In the same paper, they propose statistical (probabilistic and counter-based), geometric (distance and location-based) and graph (cluster-based) modeling solutions to apply instead of simple flooding:

Probabilistic scheme

A node forwards any new message with a probability, P. If $P = 1$, it is the same case as simple flooding. Nodes must wait a small random delay before forwarding to prevent collision problems.

Counter-based scheme

Every time a node receives a new message, it starts a counter, $c = 1$ and waits a random number of time slots. After the wait is over, it sends the message to the lower level to retransmit. If the node receives a duplicate before the message is on the air, the counter increments by one. If c reaches C, a fixed threshold, the retransmission is canceled.

Distance-based scheme

Each node is able to estimate the distance from which another node sent a message (according to the signal strength, for example). If a host receives a new message, it records this distance as d_{min} and then waits a random number of time slots before forwarding, just like the counter-based scheme. Every time it receives a duplicate from another node before retransmitting, it checks which distance is shorter and updates d_{min} with it. There is a minimum distance threshold, D, that marks the line where the coverage added by a new retransmission is negligible. If $d_{min} < D$ at some point, the node cancels the retransmission.

Location-based scheme

This can be applied if every node can get its location coordinates by means of Global Positioning System (GPS). They include it in the message before a retransmission and so, each host that receives a message can calculate the exact additional area that it would cover with a retransmission, named AC (for "Additional Coverage"). The rest is very similar to the distance-based scheme above. Instead of a distance threshold, D, an area threshold, A, is used. According to the analysis summarized before, the only sensible range for A is $0 < A < 0.61$. If after any number of received duplicates AC falls below the selected value, the node will not forward the message.

Cluster-based scheme

It adopts the idea of creating clusters from the Cluster Based Routing Protocol (CBRP) [Jiang et al., 1999]. Every node periodically emits status messages and so, each one can determine its connectivity to others. The node with the lowest ID in a group elects itself as cluster head, and the rest become cluster members. If one of them can communicate with a member of another cluster, then it is a gateway. If two cluster heads get together, the one with higher ID becomes cluster member. In the dissemination scheme, a host that receives a new message will never forward it if it is a cluster member. Cluster heads and gateways will apply one of the other four schemes.

Ni et al. compare the five schemes (in the cluster-based one, they use the location-based scheme at the gateways and cluster heads), aided by their own discrete-event simulator. They put 100 nodes in a series of maps ranging from 500 m × 500 m to 5 km × 5 km. Their transmission range is 500 m and they move through the scenario, though their mobility model and speed are not specified. Their conclusion is that, if GPS location information is available, the location-based scheme has the best performance because it reduces redundancy without compromising reachability. Otherwise, the counter-based scheme is more effective than flooding if the density is high.

In [Williams and Camp, 2002] we can find a broader comparison, as it also includes a number of cluster-based algorithms (referred to as neighbor knowledge methods) that were published after the work presented in [Ni et al., 1999]. They classify them into two categories—those in which a node locally takes a decision about forwarding and those in which the decision is taken by the previous relay. In the first group, the algorithm may use information about neighbors at just one hop, or one and two hops away. In the second group, the information about two-hop neighbors is always necessary. This knowledge is achieved by periodic *hello* packets that every node broadcasts to one-hop neighbors. The works they summarize in their paper are the following:

Flooding with Self Pruning [Lim and Kim, 2000]

Nodes collect information about their one-hop neighbors from *hello* packets. When retransmitting a message, they insert their list of neighbors in it. A node that receives a new message can then check who from its own neighbors have already received the message. If the number of neighbors that are left is over a given threshold, it forwards the message.

Scalable Broadcast Algorithm (SBA) [Peng and Lu, 2000]

In this case, vehicles retrieve information about their neighbors at one and two hops. *Hello* packets contain the ID of the issuing node plus a list of all its one-hop neighbors. Similarly to Flooding with Self Pruning, when a host receives a new message, it already knows the set of neighbors in common with the sender. If it has other neighbors apart from them, it will calculate a delay inversely proportional to the number of them. During this delay, it may still receive duplicates and update the list of uncovered neighbors. At the end, it the list is not empty, it will forward the message. This way, nodes with many neighbors can forward first and possibly inhibit retransmissions from other who have few.

Lightweight and Efficient Network-Wide Broadcast (LENWB) [Sucec and Marsic, 2000]

Nodes need information about their neighbors at one and two hops. Each host gets a priority level according to its number of neighbors. Thanks to the collected information, it also knows beforehand the priority of all its one-hop neighbors. So, when a node receives a new message, it already knows its order of precedence and if it can cover any node that the higher priority neighbors will not. If so, it will retransmit the message.

Dominant Pruning [Lim and Kim, 2000]

Lim and Kim also propose an algorithm in which the decision about forwarding is taken at the previous hop. When a node retransmits a message, it includes the list of one-hop neighbors that can forward it. This list is built using an adaptation of the Greedy Set Cover algorithm [Lovász, 1975]. The goal is to be able to cover all its two-hop neighbors with the minimum number of retransmissions from one-hop neighbors.

Multipoint Relaying [Qayyum et al., 2000]

This scheme is part of the Optimized Link State Routing Protocol (OLSR) definition. It works in the same way as Dominant Pruning with the exception of the algorithm that selects the one-hop neighbors that will forward the message, named Multipoint Relays (MPRs). In addition, the list of MPRs is notified in *hello* packets rather than in the broadcast message.

Ad Hoc Broadcast Protocol (AHBP) [Peng and Lu, 2001a]

It is very similar to Multipoint Relaying. The main differences are three. First, a node selects the forwarding neighbors, named Broadcast Relay Gateways (BRGs), at the moment of receiving a new message. Also, the algorithm discards already covered neighbors before proceeding to compute the list of BRGs. And last, the selected set is inserted in the broadcast message, as in Dominant Pruning. These measures are expected to improve the performance in highly mobile networks because when the topology changes frequently, the BRG lists can easily become outdated.

CDS-based Broadcast Algorithm [Peng and Lu, 2001b]

The same authors as AHBP present a variation in which BRGs are also assigned a priority. Each receiver removes from its cover set the neighbors of the node that sent the message and those of the higher priority BRGs, too.

Williams and Camp extensively compare a selection of the summarized protocols via simulations in ns-2. They choose the simple flooding, the counter-based scheme, the location-based scheme, Adaptive SBA and AHBP-EX. Their scenario is a 350 m $\times$ 350 m area and the nodes' transmission range is 100 m. They follow the random waypoint mobility model with zero pause time. The settings go from 327 nodes per km^2 at 3.6 km/h, to 735 nodes per km^2 at 72 km/h. The conclusion is that the probabilistic and geometric schemes are less efficient than cluster-based solutions when the node density is high. Also, those that require a random delay must adapt it to the congestion level to work better. Regarding cluster-based schemes only, mobility degrades the forwarding decision outcome when it is taken upstream instead of locally.

In summary, the work on disseminating information in MANETs is centered around alleviating the broadcast storm problem caused by simple flooding. The reason is that this type of network is generally expected to present scarce and brief network partitions, so the interest is shifted to solving the opposite problem. Different authors roughly agree on the classification that we have presented here: probabilistic, counter-based, distance-based, location-based and cluster-based schemes.

Most of the solutions for MANETs are not directly applicable to VANETs, but many can be adapted. Though the conditions in a vehicular environment are special, as we already explained in Chapter 1, many concepts from the dissemination in MANETs are still suitable. In [Chen et al., 2010], the authors present a long list of published dissemination schemes for VANETs at the date and they use a similar taxonomy: probabilistic, counter-based, distance-based, location-based, cluster-based and also traffic-based schemes. This last type contains schemes that base their decisions on parameters related with the current traffic dynamics. The main ideas under each traditional strategy remain, though the actual algorithms may vary. In the following two sections, we will discuss a few of the main works on dissemination in vehicular networks.

2.2.2 Dissemination in Interurban VANETs

In this section we compile a representative selection of significant works for the dissemination of messages intended for roadways.

Optimized Adaptive Probabilistic Broadcast (OAPB) [Alshaer and Horlait, 2005]

This dissemination scheme belongs to a general architecture for VANETs that is presented in [Alshaer and Horlait, 2004]. The authors argue for the emission of messages only in anormal events—such as sudden braking—instead of sending frequent updates. They assume the use of AODV, so the existing *hello* packets are all that vehicles need to get to know about their neighbors. Given the nature of the target messages, the main focus is to achieve a fast and reliable delivery inside the two-hop area from the source vehicle.

The forwarding strategy is a mixed probabilistic and distance-based scheme, in order to avoid the type of collisions that may happen when using distance-based only schemes. In a distance-based contention, each vehicle, D, is aware of its location and the source's, S. Before forwarding, it calculates a delay, $\Delta(t)$, so that the first vehicle to do so is the furthest one:

$$\Delta(t) = \Delta(t)_{max} \times \left(\frac{R^\epsilon - \|SD\|^\epsilon}{R^\epsilon} \right) \tag{2.4}$$

In this equation, R is the coverage range and ϵ is a value from 2 to 4, depending on the the medium's communication characteristics. The authors assume that the distribution of vehicles along the road is uniform, so they use the value $\epsilon = 2$ in order to make $\Delta(t)$ also uniform, between 0 and $\Delta(t)_{max}$.

A drawback of the described scheme is that packets from vehicles which calculate similar $\Delta(t)$ values may collide. In order to avoid this, the authors intend to reduce the group of contending vehicles to those with a high probability of reaching more neighbors (rebroadcast probability, $\overline{\emptyset}$).

Each vehicle calculates its rebroadcast probability according to the information about two-hop and one-hop neighbors it gets from AODV's *hello* packets.

For node 0, SH_o is the group of one-hop neighbors and SH_o^2 is the group of two-hop neighbors. M_{o,c_r} is the group of two-hop neighbors that can only be reached via one-hop neighbor c_r. We can calculate three different rates based on these groups:

$$Pr_0 = \begin{cases} \frac{\sum_{r=1}^{N(SH_o)} N(M_{o,c_r})}{N(SH_o)} & \text{if } \sum_{r=1}^{N(SH_o)} N(M_{o,c_r}) \le N(SH_o) \\ 1 & \text{otherwise} \end{cases} \quad (2.5)$$

$$Pr_{0_{SH}} = \frac{N(SH_o)}{N(SH_o) + N(SH_o^2)} \quad (2.6)$$

$$Pr_{0_{SH^2}} = \frac{N(SH_o^2)}{N(SH_o) + N(SH_o^2)} \quad (2.7)$$

Pr_0 is a measure of how convenient it is to use this node as a relay. $Pr_{0_{SH}}$ and $Pr_{0_{SH^2}}$ represent the proportion of one-hop and two-hop neighbors, respectively. It is important to note that these values are locally computed at each node.

Finally, the rebroadcast probability is calculated using the three former rates, as in Equation 2.8.

$$\overline{\emptyset} = (Pr_0 + Pr_{0_{SH}} + Pr_{0_{SH^2}})/3 \quad (2.8)$$

From the definitions above, we can see that $Pr_{0_{SH}} + Pr_{0_{SH^2}} = 1$ and therefore $\overline{\emptyset}$ is a linear function of degree one of Pr_0:

$$\overline{\emptyset} = (Pr_0 + 1)/3 = \frac{Pr_0}{3} + \frac{1}{3} \quad (2.9)$$

The resulting value's role is two-fold. First, it limits the number of contending vehicles. If a vehicle's $\overline{\emptyset}$ is less than a 0.5 threshold, it will not take part. In addition, this value is what determines the wait before forwarding, and not the distance to the source:

$$\Delta(t) = \Delta(t)_{max} \times (1 - \overline{\emptyset}) + \delta \quad (2.10)$$

δ is an additional random wait of milliseconds. It prevents messages from vehicles with a similar $\overline{\emptyset}$ from colliding.

The authors evaluate their approach by comparing it to reference fixed-probability and distace-based schemes. When compared to a fixed probability, this scheme presents a low redundancy (only slightly higher that that of a fixed $P = 0.2$) together with a good coverage (more than 90% of reached vehicles). According to their simulation results, this coverage is about the same as the one obtained with a distance-based scheme. The latter is slower, with a 50 to 100 ms difference in the end-to-end delay with respect to the proposed algorithm. This is reasonable, because the only vehicles that take part in the contention are those with a $\overline{\emptyset}$ value greater than 0.5. Then, $\Delta(t)_{max}$ in Equation 2.9 is always multiplied by a value less than 0.5. The authors do not evaluate the overhead of the solution in contrast with that of the probabilistic and distance-based schemes.

Multihop Vehicular Broadcast (MHVB) [Osafune et al., 2006]

MHVB is proposed as an efficient solution for the multi-hop dissemination of messages in GeoNetworking [ETSI EN 302 636-4-1, 2014]. It is focused on delivering messages in a very limited area (50–300 m) and with a reduced latency (0.1–0.5 s). These messages are not isolated warnings but status updates, so we expect periodicity. The continuous emission of information may lead to congestion in the vehicular wireless network. So, the goal is to improve the efficiency of the usage of the shared medium.

The authors propose a protocol that is made up of two algorithms—the Backfire algorithm is focused to the efficient dissemination of sent messages, whilst the Traffic Congestion Detection algorithm prevents congestion by measuring out the emission of packets.

Backfire algorithm It parts from the assumption that a normal transmission has a reception range of about 200 m, while in a dissemination we want to cover a wider radius, D_{max}. Then, if a vehicle receives a new message, it first checks if it is inside the area of interest. If so, it computes the distance to the node from which it received the message. Before forwarding, it waits an interval that is inversely proportional to the estimated distance, so that the furthest vehicle is the first to access the medium. The new retransmission will inhibit the rest of vehicles from forwarding. The authors do not provide an equation for this distance-based delay.

Traffic Congestion Detection algorithm Each vehicle is supposed to have short-range sensors that let it detect other nearby vehicles. This way, it would be easy to conclude that there is traffic congestion if the number of detected vehicles is high. Specifically, the conditions are these—(1) the number of detected vehicles is greater than a threshold, N_{max}; (2) the number of vehicles in front as well as in the back are greater than the threshold, N_{fb}; and (3) the vehicle's speed is below V_{max}. When all of them apply, the information emission period, T_{def}, must be extended. The authors propose that the new value is inversely proportional to the number of surrounding vehicles, which is contradictory, and they do not offer an equation for this value either.

Enhanced MHVB is presented in [Mariyasagayam et al., 2007] in order to include a few improvements:

- **Backfire region:** it is defined as a section rather than a circle. Vehicles whose timer have not expired before listening a new retransmission will only cancel it if the conditions in equations 2.11 and 2.12 are met:

$$|\vec{a}| > |\vec{b}| \tag{2.11}$$

$$\frac{\vec{a} \cdot \vec{b}}{|\vec{a}| \cdot |\vec{b}|} \geq \cos\theta \tag{2.12}$$

where $\vec{a}$ and $\vec{b}$ are, respectively, vehicles A and B position vectors with respect to the message origin, and θ is the backfire region angle. This lets the dissemination be flexible and directional.

- **Dynamic scheduling:** Vehicles that are 200 m or more away from the sender will forward the message immediately. This is expected to reduce the latency and save resources when covering the area between them and the origin.

The authors simulate the solution with ns-2 in a variety of scenarios—square area with random waypoint movements, a single line straight scenario and a small grid. They prove that the sectoral backfire performs relatively better than the circular backfire. The dynamic scheduling does improve significantly the success rate, understood as reaching all the vehicles in a given radius from the sender in less than a certain amount of time.

Ad Hoc and Multihop Broadcast (AMB) [Korkmaz et al., 2007]

In this work, the authors propose a two-protocol set that addresses the broadcast storm, hidden node, and reliability problems in a multi-hop dissemination of messages. It is a MAC level solution composed of AMB (*Ad hoc* Multihop Broadcast), that is totally distributed, and UMB (Urban Multihop Broadcast), that makes use of infrastructure. The first is supposed to be used only in roadways and the latter is intended for urban environments, because intersections can be supplied with wireless devices to orchestrate the dissemination.

The strategy consists in a distance-based dissemination that takes forks into consideration. It is made up of two phases—directional broadcast and intersection broadcast.

Directional broadcast The sender emits an RTB (Request To Broadcast), similar to 802.11's RTS, that includes its position and direction. Each receiving vehicle calculates the distance between the sender and itself, d. The reception range, R, is divided in N_{max} equal segments, and this distance determines in which one the vehicle is located. Each receiver sends an energy burst (channel jamming signal), called "black-burst", which length is a function of the estimated distance:

$$L_1 = \left\lfloor d \cdot \frac{N_{max}}{R} \right\rfloor \cdot SlotTime \tag{2.13}$$

$\lfloor d \cdot (N_{max}/R) \rfloor$ is the number of time slots, each of length $SlotTime$, that the black-burst will keep busy. Given that this number is proportional to the distance, the vehicle placed in the furthest segment will emit the longest black-burst. If a vehicle finds a silent channel after its black-burst, it means that it is the vehicle most apart from the sender. It then will send a CTB (Clear To Broadcast) to announce that it won the contention. When the sender receives a CTB, it sends the broadcast packet. It may happen that there are more than one vehicle in the furthest segment. Then, their black-bursts will have the same lenght and their CTBs will collide. The source vehicle will send a new RTB to start a new contention. Only the winners of the previous one will take part, by dividing their current segment in N_{max} sub-segments. If after a maximum number of repetitions there is still not an only winner, one will be chosen randomly.

Intersection broadcast In intersections inside a city, buildings will often obstruct the dissemination in other directions. We can also expect that the city government may install wireless infrastructure there, so that these devices assist vehicles in solving this problem. So there are two possible scenarios in this phase. If there is such infrastructure, it will assist the dissemination (UMB). If it does not exist, or there are not any obstacles as in open space areas, the splitting is negotiated totally ad hoc (AMB). In both situations, every vehicle must know its position, the location of intersections and where the wireless devices are in them. This is expected to be achieved by means of GPS and digital maps.

In this section, we focus only in the strategy intended for interurban dissemination.

AMB In order to split the dissemination in different directions in an ad hoc manner, we first need to define the intersection area. If the transmission range is R meters long, the area goes from $R/2\,\text{m}$ before the intersection center to $R/2\,\text{m}$ after. A directional broadcast winner that finds itself inside an intersection area becomes a *hunter*. It is the one in charge of finding the vehicle that is closest to the intersection center. So, instead of an RTB, it sends an I-RTB (Intersection RTB) and the receivers emit a black-burst that is $\hat{L}_i$ long—it grows longer as the distance to the center point, $\hat{d}$, becomes shorter. Given that (X_n, Y_n) is the position of the vehicle that is sending the black-burst, and (X_{int}, Y_{int}) is the intersection's location, $\hat{L}_i$ is computed as follows:

$$\hat{d} = \sqrt{(X_n - X_{int})^2 + (Y_n - Y_{int})^2} \tag{2.14}$$

$$\hat{L}_i(\hat{d}) = (N_{max} - 1) - L_i(\hat{d}) \tag{2.15}$$

The rest of the contention mechanism is analogous to the directional broadcast. The winning vehicle initiates a directional broadcast for each direction that is present in the intersection, except the already covered one.

The authors compare AMB and UMB with a distance-based and a random scheme. Neither of them is aware of the surrounding neighbors or the road topology. When using the distance-based scheme, a vehicle waits a lapse of time that is proportional to the distance to the source, $\hat{d}$, before forwarding a new message, as expressed in Equation 2.16:

$$WT = maxSlot \times \left(1 - \left\lfloor \frac{\hat{d}}{Range} \right\rfloor\right) \times SlotTime \tag{2.16}$$

The random scheme computes a delay before forwarding as follows:

$$WT = nSlots \times SlotTime \tag{2.17}$$

In these equations, $maxSlot$ is the maximum wait in slots, $nSlots$ is a random number in the range $[0, maxSlot]$ and $SlotTime$ is the slot duration in 802.11. $Range$ is the reception range.

Korkmaz et al. use their own simulator to try the different schemes over a 2400 m × 2400 m square area with four intersections. The performance AMB and UMB out stands the other schemes' in terms of coverage and overhead. The authors point out that this is caused by the high number of collisions, due to the existence of hidden nodes and the lack of acknowledgment, that are avoided with AMB and UMB.

Dynamic Backbone-Assisted MAC (DBA-MAC) [Bononi and Di Felice, 2007]

This MAC-level solution proactively builds a backbone (BB) by means of clustering. This allows for fast and reliable alarm dissemination through the risk zone. As secondary goals, the authors want to achieve effectiveness, fairness and scalability.

In order to create the BB, the scheme uses BEACON messages. They include the following information regarding the issuing vehicle:

$$< ID, (x, y), R, speed, dir, horizon >$$

ID is the vehicle identifier, (x, y) are its location coordinates, R is its transmission range, $speed$ is its average speed, dir is its direction and $horizon$ is the risk zone (RZ) limit.

When a vehicle does not receive any BEACON during an interval of length $RefTim$, it elects itself as member of a new backbone and broadcasts a BEACON. Vehicles who receive it and travel in the same direction are candidates to become the next hop backwards in the backbone. They use a MAC-level contention in order to select one. The objective is to single out the vehicle who is expected to be connected to the previous vehicle, $prev\_hop$, at least until the next backbone refresh, BB_REFR, but also as far as possible from it after that time. So, all the vehicles that estimate they will not remain in the transmission range of $prev\_hop$ without taking over it during BB_REFR leave the contention. The rest calculate their Fit Factor (FF) as in Equation 2.18:

$$FF(A) = \frac{dist(A, B) + \Delta\nu \times BB\_REFR}{R} \tag{2.18}$$

This parameter is an estimation of the distance between the candidate, A, and the vehicle in the BB ($prev\_hop$), B, after the BB_REFR, normalized to the transmission range. The FF is used to dynamically control the contention window of the MAC-level backoff scheme to send a CANDIDATURE message, as shown in

Equation 2.19:

$$CW = max\{0, (1 - FF(A))\} \times (CWMAX - CWMin) + CWMin \qquad (2.19)$$

If vehicle A's FF is near 1, the congestion window size, CW, will be small and hence A will have a high chance of winning the contention. When the backbone vehicle, B, receives the first CANDIDATURE message, it sends an ACK_WINNER message back to the sender. The rest of vehicles taking part in the contention abort their backoff in the moment they hear the CANDIDATURE message.

In case the vehicle heading a backbone receives a BEACON message from another vehicle in front of it, the former will immediately send a CANDIDATURE message after the SIFS interval. This way, two contiguous backbones join in a single step.

During message dissemination, the BB members have priority over using the channel, so that they get to retransmit the message. This allows for minimizing the number of forwarding nodes (given that they are BB members because of their location) and for a fast delivery of the message through space. If a vehicle in the BB sends an alert via broadcast, the next hop immediately sends back a unicast ACK (it only waits until the SIFS is over). Next, without letting go of the channel control, it broadcasts the alarm. This strategy is called Fast Multi-hop Forwarding (FMF).

If a BB node does not receive an ACK from the next hop after broadcasting an alarm, then the backbone is broken. In such a case, all the vehicles take part in a distance-based scheme. Every vehicle starts a backoff after receiving an alarm in order to broadcast it in turn. If a vehicle is a BB member, the congestion window is configured with a low value. Else, it is inversely proportional to the distance to the vehicle who sent the message, as specified in Equation 2.20:

$$CW = max\{0, (1 - dist(self, sender)/R)\} \times (CWMAX - CWMin) + CWMin \qquad (2.20)$$

The first vehicle to finish its backoff without hearing an ACK broadcasts the alarm and the rest abort their respective retransmissions. This is an adaptation of the Fast Broadcast protocol [Palazzi et al., 2007].

The authors compare this solution with other two strategies via simulations in ns-2. One of them is the Fast Broadcast protocol, as it is the base for the worst case (when there is a broken backbone). The other is a simple flooding. They use a 8 km scenario where the risk zone extends for 1 km, whereas the transmission range R is 250 m. As we could expect, the simple flooding cause a high number of retransmissions, which leads to a high percentage of collisions. The use of the backbone lets the number of retransmissions get close to the theoretical optimum and significantly reduces the number of collisions (a total of about 0.05% for a 75 vehicles/km density). The results show that this solution is able to outperform Fast Broadcast. It is also faster than the other two strategies.

Distributed Vehicular Broadcast (DV-CAST) [Tonguz et al., 2010]

This is a general purpose, network-level solution, intended for highways. The same authors later presented UV-CAST, designed for urban environments. The goal is to avoid the broadcast storm in highly populated networks, as well as the dissemination interruption in disconnected networks. The operation is based on three components: neighbor detection (to estimate a vehicle's local topology), a broadcast suppression mechanism and a store-carry-forward mechanism.

Neighbor detection It depends on information about one-hop neighbors. It consists of the tuple $< latitude, longitude, direction >$, provided by the GPS service. It is extracted from both periodic *hello* messages and specific fields in data messages. With the received information, each vehicle creates three lists:

- NB_FRONT list: neighbors in front of the vehicle (leading vehicles)
- NB_BACK list: neighbors in the back (following vehicles)
- NB_OPPOSITE list: neighbors in the opposite direction

These lists are sorted according to the most recent data and they have a limit in size, MAX_{NB} (in the authors' implementation, they have a maximum size of five positions).

For each dissemination, the issuing application defines a region of interest (ROI) that is behind the source. When combined with the neighbor data, each vehicle is able to determine the value of the following binary flags:

- Destination flag (DFlg)—the vehicle is following the originator of the message.
- Message direction connectivity (MDC)—there are at least a one-hop neighbor following this vehicle
- Opposite direction connectivity (ODC)—there are one-hop nieghbors travelling in the opposite direction

Broadcast suppression mechanism The authors present and evaluate three alternatives: weighted p-persistence, slotted 1-persistence and slotted p-persistence.

weighted p-persistence: consists in an adaptation of the well-known probabilistic flooding. It uses a forwarding probability, p, that is a function of the distance from the message source, as shown in Equation 2.21:

$$p_{ij} = \frac{D_{ij}}{R} \tag{2.21}$$

In this equation, D_{ij} is the distance between the sender, i, and the receiver, j, according to the GPS information. R is the transmission range and p_{ij} is the computed probability. In order to give precedence to the furthest vehicles, a receiver waits a preconfigured $WAIT\_TIME$ to allow for duplicates to arrive. Then, it calculates p_{ij} as a function of the distance to the closest relay. $WAIT\_TIME$ must be greater than the accumulated MAC delay experience by each node. If a given vehicle decides against forwarding but it does not detect any other doing so after $WAIT\_TIME+\delta$, it forwards with probability $p = 1$. δ accounts for the one-hop transmission and propagation delays.

slotted 1-persistence: instead of a forwarding probability, every vehicle calculates after $WAIT\_TIME$ the time slot, $T_{S_{ij}}$, in which it will try to forward:

$$T_{S_{ij}} = \tau \times N_s \left(1 - \left\lceil \frac{min(D_{ij}, R)}{R} \right\rceil\right) \tag{2.22}$$

N_s is the pre-fixed number of slots and $\tau = WAIT\_TIME + \delta$. Hearing another vehicle forwarding in an earlier time slot inhibits the retransmission.

slotted p-persistence: is similar to the *slotted 1-persistence* scheme. At the end of $T_{S_{ij}}$, however, vehicles forward with a fixed probability, p. As with the *weighted p-persistence* scheme, a vehicle that did not to forward after the timer expired waits an additional time. The authors suggest that this time could be $[N_s - 1] \times WAIT\_TIME + \delta$ ms. If even after this wait the vehicle still did not receive any duplicate, it must forward.

For the implementation of DV-CAST, the authors select *slotted 1-persistence* with $N_s = 3$.

Store-carry-forward mechanism When a new relay is not available, the last one stores the message until it finds someone that can keep forwarding it in the same direction—i.e. backwards with regard to the source vehicle. In this solution, this concept is applied by differentiating three cases of neighbor situations.

- Case I: when MDC = 1. The traffic behind is possibly dense, so the current vehicle must apply the broadcast suppression mechanism.
- Case II: when MDC = 0 and ODC = 1. If DFlg = 1 too, this means that nobody is following this vehicle but a vehicle driving in the opposite direction can be the next relay. Then, the vehicle forwards and becomes idle. But if DFlg = 0, the vehicle sets a timer after forwarding. If it detects that a vehicle traveling in the opposite direction forwards the message, it can become idle. If it hears a *hello* packet from a vehicle in the opposite direction, it forwards again and resets the timer. Lastly, if the timer expires without finding a new relay, the vehicle gives up doing store-carry-forward.
- Case III: when MDC = ODC = 0. This means that the vehicle is alone. It sets a timer and waits for one of the following events. If it hears a *hello* packet from a new follower, it changes to case I because MDC = 1 now. If it receives a *hello* packet from a vehicle in the opposite direction, it changes to ODC = 1 and hence to case II. If the timer expires, it stops the store-carry-forward.

For the evaluation, DV-CAST is compared to simple flooding and the slotted 1-persistence broadcast suppression scheme on its own by simulations on ns-2. They use a round, 4-lane roadway (two lanes per direction) with a 5 km-long ROI (less than a fourth of the circumference). The performance metrics are reliability, efficiency and scalability. The reliability measures the success as a function of the distance. The success is understood as reaching all the vehicles in the ROI or its end. The efficiency refers to the speed to cover the ROI. Lastly, the scalability is measured as the average number of generated duplicates of the same message. In addition, they comment the effect of two parameters: the frequency of *hello* packets and the inaccuracy of the GPS readings. The general conclusion is that incorporating a store-carry-forward mechanism greatly improves the success while incurring a small overhead with regard to the broadcast scheme alone.

Conclusions on Interurban Dissemination

We present a summary of the studied protocols in Table 2.1. We can see that these solutions do not assume that there will be supporting infrastructure, at least not in every roadway of the world. Hence, all of them are capable of working in a completely ad hoc and distributed manner.

There are two main interests depending on the message type—to be fast if the message is a warning, or to be efficient otherwise. For efficiency, the preferred basic multi-hop broadcast scheme is a time contention based on the distance to the previous relay. This is expected to minimize the number of necessary hops to cover the area of interest, and thus the number of duplicates. For a fast dissemination, the authors select algorithms that do not imply a time contention at the time of sending. For example, probabilistic or clustering schemes are popular. Two other features are reliability and resilience to disconnections. However, these are seen as secondary goals, as they are not considered in most works.

2.2.3 Dissemination in Urban VANETs

Most of the solutions presented so far were designed for their use in VANETs in general. However, given the especial characteristics of urban areas, the research community identified a necessity to create specific solutions for this type of scenario. The selection we present in this section consists of tailored schemes, adaptations of general schemes that are better suited for roadways, and holistic solutions.

Urban Multihop Broadcast (UMB) [Korkmaz et al., 2007]

As explained before in Section 2.2.2, UMB is part of a global solution together with AMB. We can recall that it is a MAC level solution that addresses the broadcast storm, hidden node, and reliability problems in a multi-hop dissemination of messages. It is made up of two phases—directional broadcast and intersection broadcast. Depending on the presence of infrastructure to manage junctions, the intersection broadcast is done by applying AMB (in absence of it) or UMB (when there is a

Table 2.1: Summary of Main Works for Interurban Dissemination

	Goal	Needs infrastructure	Needs beacons	Relay selection	ACKed	Store-carry-forward
OAPB, 2005	fast	no	yes	probabilistic	no	no
MHVB, 2006	efficient	no	no	distance-based	no	no
AMB, 2007	efficient, reliable	no	no	distance-based	handshake	no
DBA-MAC, 2007	fast, reliable, efficient	no	yes	clustering (backbone), distance-based	yes	no
DV-CAST, 2010	efficient, resilient to disconnections	no	yes	distance-based, neighbor detection	no	yes

managing device). UMB is supposed to be used in urban areas because the authors expect that they will be supplied with assisting infrastructure first.

So UMB is used when it is not possible to establish a direct line of sight to other streets that converge in an intersection. Buildings can block the signal, making it hard to initiate directional broadcasts to other directions without infrastructure. So, UMB relays on wireless repeaters that must be placed in intersections to manage the branching. When a vehicle gets selected during a directional broadcast an it is in a repeater's communication range, it sends the message to the repeater via unicast. If the latter keeps unavailable after a maximum number of tries, RET_{max}, the vehicle switches to AMB as a hunter node. Else, if the repeater receives the message, it will be in charge to initiate a directional broadcast in each of the other directions of the intersection.

The evaluation through simulations is summarized in Section 2.2.2, too.

Urban MHVB [Mariyasagayam et al., 2009]

The solution presented in [Osafune et al., 2006], summarized in Section 2.2.2, is adapted to urban environments. They are assumed to present intersections and a higher traffic density. So, in this case, the sender or any relay can define one or multiple sectors rather than a circle or section as the next forwarding areas. These areas are computed locally according to the estimated density. The receivers first check if they are located inside a forwarding area and, if so, start a distance-based backoff timer. The first timer to expire causes the vehicle to forward and hence "backfire" the rest.

The authors do not precise how the sections are defined, but they do provide some simulation results. They use an 802.11p implementation in ns-2 and a $1\,\text{km}^2$ square grid, in which vehicles move according to the random way point model. The solution is compared to MHVB and simple flooding in terms of several metrics, resulting in an improvement from 5% to 25%, depending on the traffic density.

Urban Vehicular Broadcast (UV-CAST) [Viriyasitavat et al., 2011]

It is a version of DV-CAST adapted to urban environments. It is intended to work in either well-connected or disconnected vehicular networks without help from fixed infrastructure. Depending on the received beacons, a vehicle can determine if it is inside a connected region or not. If it is so, it will act according to the well-connected regime, applying a broadcast suppression scheme. Otherwise, be it a boundary node or a totally disconnected node, it will enter the disconnected regime and store-carry-forward the message.

A vehicle decides if it is inside a connected region by computing the angle θ_i for all its neighbors. If we denote the sender (or relay) as S, the current vehicle as A and a neighbor as N_i, then $\theta_i = \angle S\,A\,N_i$. Hence, its value is in the range $[-\pi, \pi]$. From all the computed angles, the vehicle identifies the maximum, θ_+, and the minimum, θ_-. If Equation 2.23 is true, the vehicle is inside a connected region. Otherwise, it is a boundary node. And if it has no neighbors at all, it becomes a disconnected node.

$$|\theta_+| + |\theta_-| \geq \pi \tag{2.23}$$

If a vehicle is working in the disconnected regime, it will wait for new neighbors. When it receives a new *hello* packet, it forwards the stored message. This is repeated until it exits the area of interest associated to the message.

If a vehicle is in the well-connected regime, it enters a distance-based contention to forward the message first. The waiting time for vehicle i, τ_i, is calculated using Equation 2.24:

$$\tau_i = \begin{cases} \frac{1}{2}\left(1 - \frac{d_{i,j}}{R}\right)\tau_{max} & \text{if } i \text{ is at an intersection} \\ \frac{1}{2}\left(2 - \frac{d_{i,j}}{R}\right)\tau_{max} & \text{if } i \text{ otherwise} \end{cases} \tag{2.24}$$

where $d_{i,j}$ is the distance from the relay, vehicle j, R is the maximum transmission range and τ_{max} is the maximum waiting time. It follows that vehicles that are located at intersections wait half of the maximum wait at most. The authors do not clarify how the vehicle gets knowledge about intersections, but we could assume it gets the information from a digital map. At the end of the wait, if it did not receive any new duplicate, it forwards the message and inhibit the rest. Then all the participants become idle again.

The authors simulate this solution over a grid topology and over a real city map using SUMO [Krajzewicz et al., 2012] and ns-2. They measure the fraction of vehicles in the region that receive the message, the distance to the source, the total number of transmitted messages and the average number of duplicate messages. The results are promising but as they do not use any other scheme for reference, they are hard to put in context.

Two Angles Forwarding (TAF) [Salvo et al., 2012]

Two Angles Forwarding (TAF), along with two other variations, intend to extend the influence area of a Roadside Unit (RSU) that emits information in an urban area while meeting the following goals: to be beacon-less, to be based only on position and not to make use of any infrastructure.

The three algorithms rely on a distance-based contention and on the Triangle Forwarding Rule. This rule is based on the idea that when a vehicle receives the same message from two different neighbors, they form a triangle. The actual form for this rule depends on the variation of the protocol. It is applied each time a vehicle receives a duplicate during the distance-based contention, which uses the following equation:

$$\eta = T_{forward}(1 - d/r) \tag{2.25}$$

$T_{forward}$ is the maximum wait before forwarding, d is the distance between the receiver and the first relay from which it heard the message, and r is the reception range.

Single Angle Forwarding (SAF) The Triangle Forwarding Rule depends on the value of α. If we consider the triangle composed by the receiver, RX, the first relay, TX_1, and the new relay, TX_2, α is the vertex at TX_1:

$$\alpha = \angle RX\, TX_1\, TX_2 \tag{2.26}$$

For each new duplicate from another relay, TX_n, α is computed as follows:

$$\alpha = \angle RX\, TX_{n-1}\, TX_n \tag{2.27}$$

Each time that a duplicate is received, the vehicle checks the condition in Equation 2.28.

$$\cos\alpha > \delta_{th} \tag{2.28}$$

δ_{th} is a constant threshold. If the condition is met before the timer expires, the vehicle will not forward. Otherwise, it will become the new relay.

Two Angles Forwarding (TAF) In addition to α, the receiver also checks β, the vertex at the latest relay:

$$\beta = \angle RX\, TX_n\, TX_{n-1} \tag{2.29}$$

$$\cos\beta > \delta_{th} \tag{2.30}$$

If either Equation 2.28 or Equation 2.30 is true, the receiver must not forward at the end of η.

Multi-Two Angles Forwarding (MTAF) In this case, the cosines of α and β are computed for every possible triangle that combines two different relays from which the vehicle received the same message (not just consecutive relays).

In a previous geometric evaluation, the authors observe that MTAF offers a compromise between reached vehicles and number of retransmissions. On the other hand, TAF is the fastest from the three. The latter is tested by simulations over a Manhattan grid with dimensions 600 m×600 m. They use for a combination of SUMO, ns-2 and MOVE [Karnadi et al., 2007]. There is an RSU in the center of the grid sending packets. The performance is measured according to three metrics:

- Q_{TX}, the fraction of forwarding vehicles.
- Information coverage, the fraction of received messages by sent messages, over the time a vehicle takes to cross the map.
- The MAC collisions per vehicle and per unique message ID.

TAF outstands when compared to the distance-based scheme alone, as it offers a better Q_{TX} and information coverage.

Acknowledged Broadcast from Static to highly Mobile (ABSM) [Ros et al., 2012]

This solution is intended for general information messages and focuses on reliability and efficiency. Is is an adaptation for vehicular networks of the Parameterless Broadcast in Static to Highly Mobile ad hoc network protocol (PBSM) [Khan et al., 2008], which uses the DS-NES framework. Hence, it is based on using connected dominating sets (or CDSs) and a neighbor elimination scheme (NES).

Vehicles form connected dominated sets as in PBSM. When a vehicle receives a new message, it starts a backoff. Those who are part of a CDS wait a shorter backoff than those who are not, because they have a better connectivity. Vehicles located in intersections will end up in CDSs, given their exceptional location. For each message identifier, a vehicle creates two lists: R, containing all the vehicles that must have also received the message, and N, with the rest.

The authors assume that vehicles exchange beacons, and propose that they contain the identifiers of the last received messages for a while. These are piggybacked explicit ACKs. Vehicles in N that send a beacon with the piggybacked ACK to the given message are changed to R, and viceversa. Also, if a new neighbor appears, it is put in N.

At the end of the backoff, the vehicle checks N—if the list is not empty, it forwards the message to cover those vehicles. During the message lifetime, new vehicles that do not acknowledge its reception in their beacons may appear. They are put in N and the vehicle will forward again, until the list becomes empty again. This constitutes an implicit store-carry-forward mechanism.

The authors test the solution with ns-2 and SUMO. They use two simple scenarios—a straight 4 km roadway and a 4 km^2 crossroads. In both cases, each segment is formed by two lanes per direction. They vary the traffic density and find that the protocol fulfills the objectives: it achieves a high coverage even in sparse networks and the redundancy is almost constant, regardless of the traffic density.

Enhanced Street Broadcast Reduction (eSBR) [Martinez et al., 2010] and Enhanced Message Dissemination based on Roadmaps (eMDR) [Fogue et al., 2012]

The authors goal is to reduce the latency and increase the accuracy of the information when disseminating warnings. In addition to this type of messages, with high priority, they assume the existence of beacons, that are not disseminated and have a low priority.

eSBR is an earlier version of eMDR, and they tackle these objectives by making vehicles in intersections become relays. This is achieved with the support of GPS and digital roadmaps.

In both schemes, warnings are sent at MAC level. When a vehicle receives a new message, it forwards if its distance to the previous relay is above a threshold, or if it is in a different street. This last condition is also true if it is in the same street but located in a junction.

eMDR polishes this algorithm by adding an order in the case of vehicles in intersections. They all know their own location via GPS and that of their neighbors via beacons. So, the vehicle that is closest to the junction center forwards and the rest wait. If after 1 s they did not receive a duplicate from it, they proceed to forward immediately.

The source of the warning emits it periodically, changing the sequence number (that identifies each dissemination). The authors claim that this makes store-carry-forward unnecessary.

The simulations carried out in [Fogue et al., 2012] compare eMDR with a basic location-based and a basic distance-based scheme, FDPD (probabilistic) [Costa et al., 2006] and UV-CAST (distance-based, with a store-carry-forward mechanism). They use their own implementation of 802.11p and their Real Attenuation and Visibility (RAV) model in ns-2. The movements are managed by SUMO, where they import three different maps: $4\,\mathrm{km}^2$ areas of New York, Madrid and Rome, by topology complexity.

When looking at the percentage of informed vehicles in function of the time since the emission, the results show that eMDR reaches more vehicles than the other schemes and in less time. It comes at the cost of a higher number of duplicates than most of the other solutions.

Nearest Junction Located (NJL) and Real-Time Adaptive Dissemination (RTAD) [Sanguesa et al., 2015]

The focus of this protocol is put on safety. It is intended to warn of dangerous situations as many nearby vehicles as possible. Thus, the goals are to reduce the latency and to improve the accuracy of the information. The authors consider that an urban dissemination scheme should take into account the vehicle density and the scenario topology. Based on these ideas, they present two different solutions, Nearest Junction Located (NJL) and the Real-Time Adaptive Dissemination System (RTAD).

NJL is a simple scheme, very similar to eMDR (see Section 2.2.3) although ignoring the distance between sender and receiver. The only condition to become a relay is to be located at an intersection. As the authors point out, this is a suitable algorithm for high density situations.

RTAD, rather than a scheme, is a system for applying the most appropriate one in each situation. It relies on the Most Suitable Broadcast Selection Algorithm for this task.

The authors build this algorithm with an off-line analysis evaluates a list of strategies—a basic counter-based scheme, a basic distance-based one, eSBR [Martinez et al., 2010], eMDR [Fogue et al., 2012] and NJL.

The analysis combines different scenarios and traffic densities. Each scenario is characterized by its SJ Ratio. This is the city's ratio of streets by junctions and denotes if its topology is complex (SJ Ratio greater than 1) or simple (lower SJ Ratio). The concept of "street" is the one used in the Real Attenuation and Visibility (RAV) model by the same authors: the longest segment where two vehicles have line of sight of each other. So it could include more than one or just a section of a street as marked in a map.

The two metrics studied in the analysis are P_{inf} and M_{recv}. P_{inf} is the percentage of informed vehicles as described by Equation 2.31:

$$P_{inf}(b) = \frac{\sum_{t \in T} Inf_t(b)}{|T|} \tag{2.31}$$

where b is every broadcast scheme in the set of evaluated solutions (listed above) and $Inf_t(b)$ is the percentage of vehicles that received the message when using scheme b at instant t. M_{recv} is the number of messages received per vehicle.

The conclusions of the analysis is that for simple topologies or in high density situations, the best option is to use NJL, so that it can reduce the broadcast storm. In any other case, eMDR or eSBR are good options to reach all the vehicles as fast as possible. The remaining idea is that focusing on reducing the number of duplicates without taking into account the topology offers poor results.

RTAD uses the SJ Ratio of the current city, the traffic density estimated from the number of beacons and the thresholds offered by the Most Suitable Broadcast Selection Algorithm just explained. Depending on the combination, it applies NJL, eSBR or eMDR when a new message is received. So in summary, it is a decision rule that needs the pre-computed SJ Ratio of any given city and uses a set of thresholds computed by regression in an off-line analysis.

This system is compared with eMDR, NJL, UV-CAST, DV-CAST and FDPD [Costa et al., 2006] by simulations. The authors use a combination of ns-2 and SUMO and incorporate a Downtown Model for realistic traffic mobility and the RAV propagation model. They test the solutions over several real city maps via OpenStreetMap[2]. The advantage in the face of static schemes, like NJL and eMDR, obviously, is the ability to adapt to different density situations. For low densities, the performance is the same as eMDR, for it is the applied protocol in such a case. For high densities, RTAD combines the best of eMDR (high P_{inf}) and NJL (few messages). With regard to adaptive schemes, it reaches more vehicles than UV-CAST in less time. RTAD avoids broadcast storms in high traffic density better than DV-CAST. And it outperforms FPDP in general.

Conclusions on Urban Dissemination

Inside urban areas, buildings suppose the main problem. The solutions in this area propose schemes that will maximize the circulation of the message through the whole set of streets in the region of interest. The selection of works explained in this section use different methods for detecting junctions or other streets: digital maps, reception angles and relative location of neighbors.

The focus is set, apart from coverage, on the efficiency. This is due to the high density of vehicles in cities, together with usually lower speeds. The latter implies lower danger in the case of accident and a longer time before reaching the place of the

[2] `http://www.openstreetmap.org`

Table 2.2: Summary of Main Works for Urban Dissemination

	Goal	Needs infrastructure	Needs beacons	Relay selection	Junction detection	ACKed	Store-carry-forward
UMB, 2007	fast	yes	no	distance-based	digital map	handshake	no
Urban MHVB, 2009	efficient	yes	yes	distance-based	neighbor density	no	no
UV-CAST, 2011	efficient, resilient to disconnections	no	yes	distance-based	digital map	in beacons	yes
TAF, 2012	efficient	no	no	distance-based	reception angles	no	no
ABSM, 2012	reliable, efficient	no	yes	clustering (CDS construction)	-	in beacons	yes
RTAD, 2015 (eSBR, eMDR, NJL)	fast	no	yes	location-based + distance thresholds	digital map	no	no

event. Because of this, most solutions use a distance-based contention or clustering, to select as few relays as possible. There are other works that have their focus on a fast dissemination. These use location-based solutions and binary thresholds in order to take advantage of junctions and to avoid a time-consuming contention.

There is discussion regarding disconnected areas that result from buildings blocking the dissemination. Some authors propose using mechanisms to overcome disconnections, while others argue that it should be the source who repeats its message periodically.

In contrast with the assumption for roadways, cities are expected to get some infrastructure deployed in them over time. So, dissemination solutions are still capable of working without the aid of any fixed device but some also consider this possibility.

A summary of the main works in this area and their characteristics is in Table 2.2.

2.2.4 Conclusions on Dissemination Schemes

We have given a glimpse on a varied selection from the literature in dissemination schemes for VANETs. We have seen how the research community has gone from general solutions, better suited and mainly tested on roadway scenarios, to specific schemes for cities. As we will develop in the following chapters, we have followed a similar path—we begin with a general scheme from the state of the art in MANETs, adjust it for roadways, and then create an adaptation for urban scenarios.

As we can see in the summary tables 2.1 and 2.2, authors agree in three relevant metrics for evaluating a multi-hop broadcast scheme: coverage, redundancy and delay. It is impossible to achieve the optimum for all of them. Each researcher puts emphasis on one of the three depending on the final goal (reliability, efficiency or speed, respectively) at the cost of the other two. Reliability seems to be secondary to most applications, and most authors concentrate on speed or efficiency.

A fast dissemination is interesting mainly for safety-related applications. For example, when warning upcoming vehicles of a sudden brake. Then, frequent status messages are exchanged in order to create a backbone or cluster-based structure. Members of the backbone or cluster heads are preselected to forward a packet immediately in the event there is one, like DBA-MAC and ABSM. If reliability is not necessary, a fast algorithm like a probabilistic scheme like in OAPB, or a binary decision like in RTAD, are also applicable.

Efficiency is important in most cases, especially if the application is delay-tolerant. The shared bandwidth is a limited resource and vehicular networks can get very crowded (for example, in cities or traffic jams). Then, broadcast suppression techniques help in reducing the number of sent duplicates. A popular algorithm for this task is the distance-based scheme. It minimizes the number of hops that are necessary to cover a given area, and therefore the number of duplicates, too. It is present in many works commented in this chapter: MHVB/Urban MHVB, AMB/UMB, DBA-MAC, DV-CAST/UV-CAST and TAF.

Reliability can be achieved by implementing some kind of acknowledgement system, like the handshakes in AMB/UMB or clustering like in DBA-MAC and ABSM. In line with this goal, a few of the works presented here try to cover more nodes by applying a store-carry-forward mechanism that helps alleviating the effects of network partitioning. We have seen this approach in DV-CAST/UV-CAST and in ABSM, too.

Urban scenarios adds the problem of signal bouncing and blocking because of obstacles like buildings. Solutions for this type of topology focus on this task. With the only exception of ABSM, whose relay selection mechanism already promotes vehicles in intersections, all of them incorporate a junction detection mechanism. Some rely on digital maps, like UMB, UV-CAST and RTAD. Others use different metrics, like the neighbor density in Urban MHVB or the reception angles in TAF.

In our search, we have not found a single solution that meets all our initial requirements: to prioritize efficiency, to be independent from infrastructure and from status updates, and to implement some mechanism that lets the message travel through disconnected regions. However, we have identified some hints as the best

Table 2.3: Summary of Main Works for Interurban Dissemination – II

	Simulator	Movement generator	MAC	Scenario	Comparative
OAPB, 2005	ns-2	own impl.	802.11	straight segment	probabilistic, distance-based
MHVB, 2006	ns-2	own impl.	802.11	square area, straight segment, small grid	–
AMB/UMB, 2007	own impl.	own impl.	AMB/ UMB	grid	distance-based, random wait
DBA-MAC, 2007	ns-2	own impl.	802.11	straight segment	Fast Broadcast, simple flooding
DV-CAST, 2010	ns-2	own impl.	802.11a	circumference	simple flooding, slotted 1-persistence

Table 2.4: Summary of Main Works for Urban Dissemination – II

	Simulator	Movement generator	MAC	Scenario	Comparative
Urban MHVB, 2009	ns-2	unknown	802.11p	grid	MHVB, simple flooding
UV-CAST, 2011	ns-2	SUMO	802.11p	grid, real city maps	–
TAF, 2012	ns-2	SUMO	802.11p	grid	distance-based
ABSM, 2012	ns-2	SUMO	802.11p	straight segment, small grid	DV-CAST, PBSM-2t, PBSM-1p
eMDR, 2012	ns-2	SUMO	802.11p	real city maps	location-based, distance-based, FPDP, UV-CAST
RTAD, 2015	ns-2	SUMO, Downtown Model	802.11p	real city maps	eMDR, NJL, UV-CAST, DV-CAST, FPDP

basic dissemination scheme for efficiency and the importance to acknowledge receptions for store-carry-forwarding messages.

Regarding evaluations, we have collected the most relevant data in tables 2.3 and 2.4. The first impression is that almost all the works were evaluated using the ns-2 simulator.

We can see that the early works use a few different settings, mainly straight segments and occasionally also small grids. These are the solutions that were created for roadways or for any type of scenario, listed in Table 2.3. The protocol used in the MAC layer is 802.11 in its implementation for the ns-2 simulator, while the mobility is created ad hoc by the authors.

There are clear differences in Table 2.4. The first is in the employed scenarios—Manhattan grids and real city maps. The usual generator of vehicles movements is SUMO and the PHY/MAC layers are simulated with the 802.11p module for ns-2, that was first introduced as an extension in 2007 [Schmidt-Eisenlohr et al., 2007].

From the protocols chosen by authors to compare their solutions, we identify DV-CAST, together with its urban counterpart, UV-CAST, as a popular reference. They include many of the features we want for our own schemes, that we already mentioned above. Thus, these are the solutions that we are going to use in order to assess our work, too.

2.3 Conclusions

We have already commented our conclusions in Sections 2.1.3 and 2.2.4, so we just summarize the main points here.

First, we have offered a brief description of the standardization efforts in the USA and the European Union regarding the design and launch of communications among vehicles and between them and infrastructure. The American standard, DSRC, leaves multi-hop dissemination to IPv6. The European approach, ITS, includes some algorithms for this task that were standardized in 2014.

This situation led to the proposal of solutions from the research community. At first they were oriented to a general scenario and tested mainly on simulated highway scenarios. In the last years, specific solutions, that take into consideration the special characteristics of urban environments, are appearing.

In the following chapters, we explain the work for this dissertation, that has been done in parallel to this last generation of solutions. We start by identifying the main differences between the two types of scenarios, in order to create schemes that are adapted to each of them.

Chapter 3

Target Scenarios and Tools

As we have already commented in the previous chapters, we deal with two very different target scenarios. We need to take their special characteristics into account during the design of a solution and at the time of assessing its performance via realistic simulations. In the next sections we list the main mobility model families and the tools we have used for the evaluations.

3.1 Target Scenarios

There are two types of vehicular scenarios generally recognized—roadways and cities. We explain their differences with regard to connectivity, and some of the main works that try to model the traffic in them.

3.1.1 Differences between Roadways and Cities

The two main differences between these two types of scenarios are the topology and the consequent range of movements of vehicles in them. Their movements in roadways are restricted to a one-dimensional pattern, while urban areas allow bi-dimensional trajectories [Viriyasitavat et al., 2009]. Hence, routing and dissemination algorithms cannot be applied interchangeably.

The same authors present in [Viriyasitavat et al., 2011] a list of routing challenges in urban settings that are not present in roadways, that we summarize here:

- **Direction of the message and determination of the ROI.** The authors consider that the definition of the ROI depends on the type of application and the vehicles that may be interested in the information. Also, the direction of the message should correspond with the direction of the targets, so defining it may pose a privacy risk.

- **Changes of vehicle direction.** A vehicle may change its current direction at any intersection. This is a problem for choosing nodes for store-carry-forwarding—the selected relay may not go towards the desired direction at some point. The conclusion they reach is that typical mechanisms for roadways are not applicable to this type of scenario.

- **Multiple points to enter or exit the ROI.** As there will be several streets going through the bi-dimensional ROI, vehicles can enter or exit them at different points around the edge. The main implication is that we cannot consider that a dissemination is complete when the message reaches the edge, because it may have covered only a sector of the area of interest.

- **The coverage of a vehicle depends on its location.** The authors point out that vehicles at intersections can connect with vehicles in other streets, while others can only reach vehicles behind or in front of them. They suggest that routing and dissemination protocols should bear in mind this difference in order to take advantage of it.

In addition, they extract two important observations about the special connectivity conditions in urban VANETs from their study in [Viriyasitavat et al., 2009]. First, that the broadcast storm and the disconnected network problems are present at the same time. This is because vehicles are not evenly distributed in the scenario, forming dense groups disconnected to the others. Second, that it is usual the existence of path redundancy—there are multiple ways to connect one vehicle with another. This can help improve the robustness of routing or dissemination protocols.

3.1.2 Modeling of Traffic Dynamics

We need mobility models that mimic traffic's true behavior. Roadways can be described with a relatively simple model because of their topological simplicity and the limited variety of movements. Urban areas contain street networks that are much more complex. Every vehicle can perform a variety of movements like taking over, turning at intersections, parking, waiting at traffic lights, yielding, etc. Researchers keep working on traffic models that can realistically describe the movements of vehicles in both scenarios.

There are four types of vehicular mobility models, according to [Harri et al., 2009]: synthetic models, survey-based models, trace-based models and traffic simulators-based models.

Synthetic Models The objective is to develop mathematical models that try to replicate a real physical effect. We can divide this group in five classes, according to [Fiore, 2008]: stochastic models (random movements), traffic stream models (based on hydrodynamics), car following models (understanding one driver's behavior as a consequence of its preceding traffic), queue models (taking streets as FIFO queues) and behavioral models (movements are determined by behavioral rules). Some examples of models in this group are adaptations of the Random Waypoint like [Hsu et al., 2005] and the behavioral model presented in [Musolesi and Mascolo, 2006].

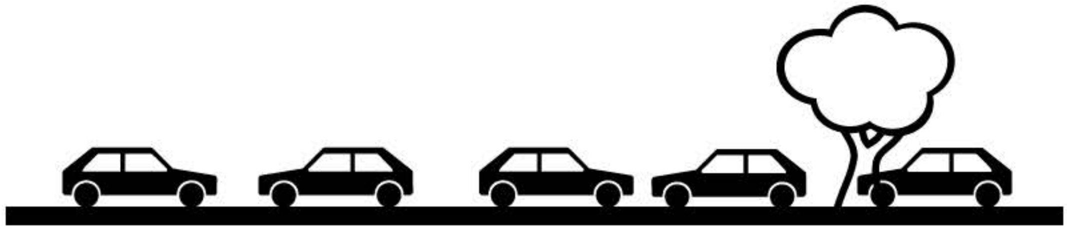


Figure 3.1: Schematic representation of a roadway scenario.

Survey-Based Models A great source of information about macroscopic mobility is the collection of real data via surveys. These generic mobility models combine different statistics about people's habits. Two examples of this type of model are the Swiss MMTS [Naumov et al., 2006] and the previous work to the American TRANSIMS [Beckman et al., 1996]. However, these approaches can only describe mobility in a general way. If we need a realistic microscopic model, we have to use a complex synthetic model as our basis and tune it via surveys.

Trace-Based Models A different take from working on a mathematical model and then calibrating it with real data, is to extract the model directly from mobility traces. This method has become popular due to several collection campaigns, but it also poses a problem: it is impossible to extract models of patterns not observed in the traces. For example, data collected from a fleet of buses would provide for a good public transportation model, but it could not be extrapolated to private traffic.

Traffic Simulator-Based Models Finally, we can find simulators for urban traffic engineering, like TRANSIMS [Beckman et al., 1996] or SUMO, that are the result of refining synthetic models with data from surveys or real traces. These simulators are able to model urban microscopic traffic and many other characteristics like noise level or pollution. In the last years, they have gained significance in the simulation of VANETs, as researchers have created tools to make them communicate with network simulators.

3.1.3 Traffic Models for Roadways

We understand roadways as any road outside an urban area. Typically, vehicles travel in both directions. Roadways have at least one lane per direction. We analyze now three of the most relevant studies about modeling the movement of vehicles in roadways.

One of the first works on this topic is based on a study of empirical data from a dual-loop detector along the US I-80 freeway [Wisitpongphan et al., 2007]. They observe that speeds follow a normal distribution, with an average of 10 m/s (36 km/h) during rush hours and approximately 30 to 32 m/s (108 to 115 km/h) during non-rush hours. The inter-vehicle spacing can be approximated as the product of the vehicle speed and the road-level inter-arrival time. This article focuses on sparse networks, so their study of the inter-arrival time is limited to the hours of low traffic volume. According to their data, the traffic is sparse when the flow is up to 1000 vehicles/h (around 9 vehicles/km at 115 km/h). In light traffic, the inter-arrival time approximately follows an exponential distribution. When the traffic volume is higher, the vehicular network is expected to be connected and the exponential approach is not valid any more. The authors suggest that the distribution for high densities could be approximated as a log-normal.

Other authors [Gramaglia et al., 2011] work with data from several highways around Madrid outskirts, provided by the Spanish *Dirección General de Tráfico* (DGT). These traces register the moment vehicles pass by and their speed during a whole day. It is worth noting that neither of the traces contains rush hour traffic densities. Their study shows that the arrival times in moderate traffic are not independent and identically distributed (i.i.d.). In those cases, vehicles move in bursts, where a driver finds overtaking difficult and the speed of the vehicle ahead limits its own speed. The authors agree that the exponential distribution models well the isolated traffic. However, for burst traffic, they reach the conclusion that the inter-arrival time distribution is normal. They are able to establish a threshold between exponentially and normally distributed inter-arrival times at 2.5 s. Finally, they propose a mixed distribution (exponential plus log-normal) to model the inter-arrival time.

In [Cheng and Panichpapiboon, 2012], the authors use a similar set of traces from the Berkeley Highway Laboratory. Based on this data, they deduce the distance between vehicles. They divide the trace in 24 1-hour sections. The exponential distribution is a good approximation for the sections with lower traffic density (1.00 am to 5.00 am, with about 0.005 veh./m). For higher densities, the exponential distribution would underestimate the true distance between vehicles. The authors conclude that the best fitting distribution for light to moderate traffic is the Generalized Extreme Value (GEV) [Resnick, 1987]. However, the article does not include a model that would relate the traffic density or flow to any of the two distributions, nor a characterization of the rush hour traffic.

So, based on these studies, we are going to assume that inter-arrival times, or the distance between vehicles, are exponentially distributed for low traffic densities. For higher densities, the inter-vehicle space will be approximately normal.

3.1.4 Traffic Models for Urban Areas

As we have already mentioned, urban scenarios are complex to model. The most popular type is the Car Following (CF). It consists of a set of rules that describe the position and speed of any vehicle, in function of its own speed, that of the preceding vehicle, and the distance between them [Harri et al., 2009]. There are many subtypes of the CF model, the cellular automaton (CA) possibly being the most used one. The interest of this type of model is that it is relatively simple but it is able to model a complex behavior with a low computational cost. This makes possible to simulate networks in a reasonable amount of time. There are several simulators that use this approach. In this section we are going to present three of them that are very popular in VANET simulation: the Manhattan model

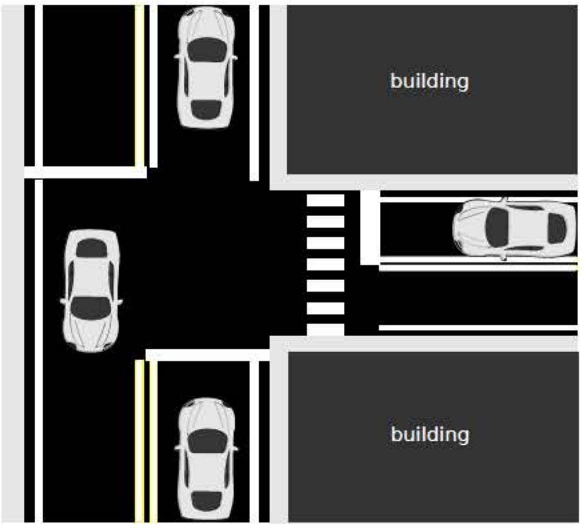


Figure 3.2: Schematic representation of a small urban scenario section.

from the IMPORTANT framework [Bai et al., 2003], the Street Random Waypoint (STRAW) [Choffnes and Bustamante, 2005] and the Simulation of Urban MObility (SUMO) [Krajzewicz et al., 2012].

The framework for analyzing the Impact of Mobility on the Performance Of RouTing protocols in Ad hoc NeTworks, known as IMPORTANT, became a relevant tool for the simulation of vehicular networks in ns-2 since its publication. It was conceived as the consequence of the Random Waypoint (RWP) model inability to realistically reproduce vehicular movements. The authors wanted to assess the impact that a mobility model has on the evaluation of a routing protocol and caused the adoption of better models. Specifically, the research community started using the three mobility models defined in the framework, that were easily available via a generator tool. These three models are the Reference Point Group Mobility (RPGM) Model, the Freeway Mobility Model and the Manhattan Mobility Model. RPGM moves vehicles in clusters, while the other two implement the CF approach. The Freeway model proposes the use of "maps", created by defining freeways. They can have any number of lanes, in any of the two directions, and their topology can be specified with sets of coordinates. Each vehicle movements are restricted to its own lane. The Manhattan model is similar, with some special characteristics to better simulate urban environments. Lanes form a grid and when a vehicle reaches an intersection it chooses probabilistically to turn left or right, or to continue in the same direction.

The motivation of STRAW is the same as above—its authors wanted to create a mobility model that could substitute RWP in order to better assess the performance of VANET protocols. This mobility model also constrains the movements of each vehicle to its own lane but, instead of custom maps, it uses real city maps from the US. This model considers that, in addition to turning at intersections, vehicles may have to decelerate and stop before them because the new street segment is full, there is traffic control—either a stop sign or a red stoplight— or if the preceding vehicle stops. Regarding routes, it implements two different models: simple inter-segment mobility (Simple STRAW) and mobility with origin-destination (OD) pairs (STRAW OD). The first decides turning at intersections based on the configured probability, and the latter follows the shortest path between or origin and the destination.

The project named SUMO started in 2001 and has evolved into a suite of tools for traffic modeling and simulation. One of the main interests of the authors in making it open source and publicly available was making it a popular framework and gaining support from other institutions. Since 2006, SUMO has an extension named TraCI that lets it bi-directionally connect with a network simulator. Thanks to all this, it has become the main tool for the simulation of urban VANETs nowadays, as we could check in Chapter 2. The mobility model itself is more sophisticated than the two works above, as it also includes changes of lane and overtaking. Regarding maps, they can be imported or manually configured. This allows the creation of small test scenarios and the use of real city maps. At the time of departure, each vehicle is given the list of connected edges from origin to destination that compose its route. There are different tools that generate routes suitable for SUMO.

As most other current authors, we are going to use SUMO for our simulations for its many advantages. The specific details about our simulations appear in the next section.

3.2 Tools

Now that we have an understanding of the modeling of both environments, we proceed to explain the list of tools we have selected for simulating them. We have decided on them in order to make it as realistic as possible. We end this section explaining the metrics that the research community uses for assessing this type of schemes and the exact meaning in our evaluations.

3.2.1 Simulation of Vehicle Traffic in Roadways

We test and assess the different steps of our design for roadways via simulations in ns-2. At the time, its version 2.34 was the first to include 802.11p simulation support [Schmidt-Eisenlohr et al., 2007], as well as the Nakagami radio propagation model, suggested as the best for realistically simulating VANETs [Hartenstein and Laberteaux, 2008].

We use the configuration values for the radio propagation in a highway (Highway 101 in the Bay Area of the USA), as well as for 802.11p, detailed in [Taliwal et al., 2004]. The complete network characterization is contained in Table 3.1.

Regarding the scenario, we always place the vehicles in a straight roadway with two lanes, one for each direction. The inter-vehicle space is exponentially distributed according to the traffic density ρ and the lessons learned in the previous section. According to [Gramaglia et al., 2011], an inter-arrival time of 2.5 s marks

Parameter	Value
MAC	802.11p
Frequency band (10 MHz channel)	5.900 GHz
Propagation model	Nakagami
Transmission power	0.1 W
Antenna gain	1 dB
Sensitivity	−94 dBm
SNR	40 dBm
Thermal noise	−99 dBm
Communication range (r)	232 m
Encoding	OFDM
Modulation	BPSK
Bitrate	6 Mbps

Table 3.1: Network parameters in the roadway simulations.

the threshold between exponentially or normally distributed times. If we assume that the average speed is around 100 km/h during non-rush hours, as pointed out in [Wisitpongphan et al., 2007], the threshold can be translated into an inter-vehicle space of 69 m or a traffic density of 14.4 vehicles/km.

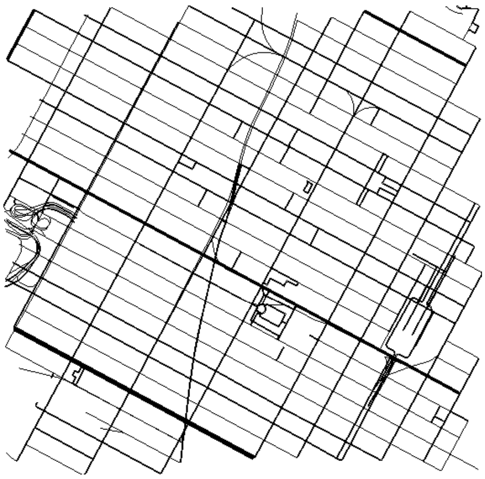
So, when we use traffic densities below this threshold, we apply an exponential distribution with mean $1/\lambda = 1/\rho$ to assign inter-vehicle spaces. For higher densities, we apply an horizontally shifted normal distribution. Again, its mean $\mu = 1/\rho$ but we need to define an appropriate standard deviation. The graph in [Gramaglia et al., 2011]'s Figure 6(a) shows the histogram of inter-arrival times below the 2.5 s threshold (corresponding to high traffic volume). The fitted normal has its mean right at 1.25 s and it obviously expands up to 2.5 s (the threshold). Given that 99% of the points under a Gauss bell are in the range $\mu \pm 2.58\sigma$, we can calculate this sample standard deviation:

$$s = (2.5 - 1.25)/2.58 = 0.48 \tag{3.1}$$

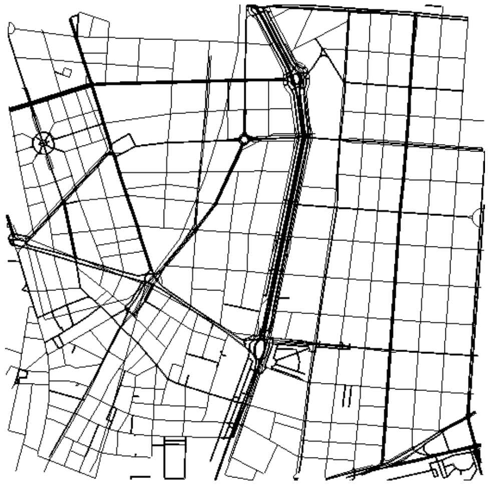
So, for an average inter-arrival time of 1.25 s (about 30 vehicles/km at 100 km/h), the expected standard deviation is 1.25 s (13.5 m between vehicles). If we rise the traffic density to 40 vehicles/km (and keep the average speed at 100 km/h), the inter-arrival time is 1.1 s, which is still close to the sample average above. So, to simplify, we use a fixed standard deviation of 0.48 s in our scenario generator. The mean will be inversely proportional to the traffic density.

We assign each vehicle a random speed. It follows a truncated normal distribution, according to the findings in [Wisitpongphan et al., 2007]. The speeds we use are in context with the typical speed limits in the European Union roadways—from 60 to 120 km/h. We adapt the average speed to the traffic density. So, for very sparse traffic (below 15 vehicles/km), the average speed is 120 km/h. Moderate traffic reaches an average of 100 km/h.

Once all the vehicles are moving along the roadway in both directions, one fixed



(a) New York (USA)



(b) Madrid (Spain)

Figure 3.3: Simulation scenarios for the urban environment.

sender broadcasts a message. This message is forwarded according to the selected scheme in each simulation batch.

3.2.2 Simulation of an Urban Environment

We have chosen Veins [Sommer et al., 2011b] as our simulation framework. It is a hybrid VANET simulator that joins the SUMO traffic simulator, that was created for the realistic recreation of urban traffic, and the OMNeT++[1] network simulator. OMNeT++ is a widely used tool among MANET researchers and, though it meant a depart from ns-2 for us, it was worth the change to take advantage of SUMO. The Simple Obstacle Shadowing propagation model for building shadowing [Sommer et al., 2011a] is also available in the Veins framework, making it the perfect tool for recreating urban environments.

In addition, we were able to use other tools that can be applied to Veins: VACaMobil [Baguena et al., 2013] let us maintain a constant traffic density throughout every run of the simulations and OpenStreetMap provides real maps that can be imported into SUMO.

As discussed in [Fogue et al., 2012] and [Viriyasitavat et al., 2011], results can be quite different depending on the urban scenario in which the dissemination happens. We have used two different areas of 2 km × 2 km, shown in Figure 3.3. The Manhattan, New York map is almost a grid, while the area around the Castellana Street in Madrid is more irregular.

Finally, we have configured the network parameters according to typical values described in [Brakemeier, 2009]. The specific overall configuration is listed in Table 3.2.

[1] `http://www.omnetpp.org`

Parameter	Value
MAC	802.11p
Frequency band (10 MHz channel)	5.900 GHz
Propagation model	Simple Obstacle Shadowing
Transmission power	1 W
Sensitivity	−77 dBm
SNR	13 dBm
Thermal noise	−104 dBm
LOS communication range (r)	232 m
Modulation	QPSK
Bitrate	6 Mbps

Table 3.2: Network parameters in the urban simulations.

3.2.3 Metrics for the Performance Evaluation

We can group the metrics we use in this study into three categories: success, overhead and latency. They are the categories that researchers use to assess the performance of solutions for information dissemination.

Success The final goal of a multi-hop broadcast is to reach as many nodes as possible in a given area. We assess the success with two different metrics: The *delivery ratio* is the average amount of vehicles that receive the message. We define the *long-reach success* as the portion of cases from all the executed simulation runs, where the dissemination goes further than the second hop—i.e. the message leaves the source area. We will represent it normalized to that of a simple flooding in the same situation.

Overhead A high overhead is undesirable, as it occupies the limited shared bandwidth with useless data. It can be measured with the *redundancy ratio*, that we define as the ratio of sent duplicates to the total of vehicles that received the message. We can also see it as the ratio of vehicles that act as relays to the number of receivers. Another metric that shows the consequence of the redundancy is the *number of lost packets*, as congestion leads to this effect.

Latency The third performance indicator is the latency of the scheme. We may use the per-hop delay or the end-to-end delay. The *per-hop delay* accounts for the distance-based and MAC contentions and for the propagation time. The *end-to-end delay* is averaged over all the receivers, may they be at one or several hops away from the source.

Depending on the upper application, it may be preferable to optimize one or two of them. In our case, our priority is to reduce the overhead while trying to reach the maximum coverage of receivers. Achieving the optimum of the three is near to impossible, because we can only improve one at the cost of the others.

3.3 Conclusions

In this chapter, we have presented the two scenarios we are going to work with and the main tools for it. We need to understand the characteristics of each environment, in order to design and realistically test solutions that will adapt to its necessities. We have presented a discussion about the differences between them according to renowned authors in the subject.

It becomes clear that it is important to understand the mobility of vehicles in each scenario in order to create and evaluate solutions for them. We have reviewed some of the main works on modeling the traffic of vehicles in roadways at a macroscopic level. We can identify two regimes—dense and sparse traffic situations. Several authors have pointed out that these regimes show different behaviors and hence we cannot model them in the same way. Vehicles in dense traffic scenarios usually form a connected network and the space between consecutive vehicles is approximately normally distributed. Sparse traffic leads to disconnected groups of vehicles, and their inter-space distribution is exponential.

Then, we have three popular mobility models for urban traffic. Inside cities, traffic modeling is much more complex than in roadways, because there are numerous options and factors that can affect vehicles movements. For this reason, the most common mobility models are microscopic. Specifically, the car following (CF) model is possibly the most widely used one and it is the base of many traffic simulators. We have presented three frameworks that implement mobility models based on CF: IMPORTANT, STRAW and SUMO. The last one has evolved and gained in popularity, and is now the mobility simulator in most current works.

Knowing all this, and after reading an extensive amount of works on solutions for both types of scenarios, we identified a series of tools that we are using in this dissertation for evaluating our progress. We have presented the simulator and configuration for each type of scenario, that respond to the different characteristics and our own necessities and resources for simulations. We have also explained the three areas of interest when evaluation the performance of a dissemination scheme—success, overhead and latency—and which metrics we will use to measure them throughout this dissertation.

The next two chapters contain the actual design, study and assessment of our solutions for roadways and cities, in which we make use of the resources explained here.

Chapter 4

Selection of a Basic Dissemination Scheme

In this chapter, we investigate which basic dissemination scheme from the existing literature is the best fit for our requirements. Specifically, we want to find one that causes the minimum number of duplicates, in order to be as efficient as possible.

As we could see in Chapter 2, the performance results of the different solutions have been obtained by means of simulations with different tools and mobility models. This makes it difficult to tell which one leads to the best performance. So a natural first step for our research was to establish a general comparison of the basic dissemination techniques.

4.1 Set of Basic Schemes

We part from the taxonomy for VANET dissemination schemes in [Chen et al., 2010] that we commented in Chapter 2: probabilistic, counter-based, distance-based, location-based, cluster-based and traffic-based.

All of them can be executed without any knowledge about nearby vehicles, except for cluster-based forwarding. As we explained in Chapter 2, nodes that apply this scheme use information about their neighbors to form groups and select the best relay from each one. As vehicular networks pose a very dynamic environment, such information is highly volatile. Each vehicle must broadcast status updates (also called beacons or *hello* packets) frequently.For these reasons, we discard using a cluster-based technique for our solution.

From the classification above, we also discard location-based flooding for this study. The algorithm is very similar to the distance-based one, as it computes additional covered areas instead of working with distances. It does not add much information and its computational cost is higher.

So, the selected basic techniques, together with our specific implementation, are the following:

Simple Flooding: Vehicles will forward every incoming message that is new to them. In order to decide whether the message is new or not, every node must keep a list of received messages. The rest of the implementations are built upon this base. This scheme is used as a reference for its maximum connectivity and redundancy.

Probabilistic Scheme: Vehicles decide whether to re-broadcast any new message by using a previously fixed probability of forwarding, P (using $P = 1$ is the same as simple flooding). For this study we select a few values in a wide range—0.75, 0.5 and 0.25.

Counter-based Scheme: Upon the reception of a new message, a vehicle waits for duplicates during a random assessment delay (RAD). This interval is chosen from an uniform distribution between 0 and w seconds. When its timer expires, the vehicle forwards the message if the total number of duplicates is less than a configured count threshold, C. We use $w = \{0.01, 0.1\}$ and $C = \{2, 3, 4\}$. We have selected the two values for w from the set of tested ones in [Williams and Camp, 2002] (RAD Tmax in that paper). Regarding C, the article [Ni et al., 1999] proves that a value of 3 or 4 is an appropriate choice, at least for MANETs, and we have also considered the minimum value, 2.

Distance-based Scheme: We use a variation of the distance-based scheme that is very common in the solutions for VANETs: the distance to the sender is used to calculate a delay the node must wait before forwarding. In Chapter 2 we could see this approach as part of the schemes presented in [Alshaer and Horlait, 2005], [Osafune et al., 2006], or [Tonguz et al., 2010], to name just a few. Our personal implementation is as follows. When a vehicle receives a new message, it awaits duplicates for a fixed period, W. After a first test run with a high traffic density (30 vehicles/km), the arrival time at any given node between almost simultaneous duplicates was always under 2 ms, so we have used this value. Afterwards, the forwarding delay, t_w, is calculated with this equation:

$$t_w = T_{max} \times (1 - d_{min}/r) \tag{4.1}$$

Here, r is the expected reception range and d_{min} is the distance to the closest relay. The maximum per-hop wait, T_{max}, is set to 10 ms.This equation gives priority to the most distant vehicle in the coverage area. A vehicle near the relay will have to wait T_{max} before forwarding, whereas a vehicle close the edge of the coverage radius will wait very little time. If a node hears another one doing so before itself, it drops the message.

Traffic-based Scheme: A way to improve the selection of relays is to introduce information about the traffic conditions into the decision. If the node has some knowledge of the traffic context, it could estimate how efficient it would be to forward a message. We create a scheme for this category, too, in which the vehicle must know the speed limits of the road it is in. Those that travel at non-average speeds should become the relays because they are more likely to meet new neighbors than the rest. So, a vehicle that receives a new message decides to forward it if its speed is either (a) lower than $v_{min} + 1/3 * (v_{max} - v_{min})$ or (b) higher than $v_{min} + 2/3 * (v_{max} - v_{min})$. In this formula, v_{min} and v_{max} are, respectively, the minimum and maximum allowed speed in the road.

Any of the techniques described above can be applied to all the vehicles in the road or just to those traveling in the same direction as the message. The latter makes sense as it will always carry the message towards its destination. However, it has two problems: First, counting with less vehicles to help in the dissemination leads to bigger gaps between the involved ones. This could create unnecessarily disconnected groups. The second and most important one is how to disseminate a message in one-way roads. The vehicles potentially interested in the message are usually those that travel towards its source point and they would not receive it. Therefore, we involve all the vehicles in the road despite their direction. This resolution is maintained throughout all the dissertation.

4.2 Performance Analysis

We compare the described schemes in a roadway scenario for being the simplest. In Figure 4.1, we show a schematic representation of the scenario for the simulations. We use the configuration explained in Section 3.2.1. The specific settings for these simulations are listed in Table 4.1. We use a straight roadway scenario of 4 km, with a fixed sender in the middle. We define the ROI by means of a radius around the sender, R_{target}, of 2 km. Given that the reception range is 232 m, we ensure that there must be a multi-hop dissemination in order to reach all the vehicles in the scenario. We use three different traffic densities, from sparse (20 vehicles/km) to dense (40 vehicles/km), in order to check the performance under different conditions. Finally, the chosen payload is 16 B because we wanted very short packets that would not add to the different resulting delays.

The metrics that we use are the following: first, the delivery ratio. We calculate it by dividing the number of reached vehicles by the total amount of them at the moment of the emission. As we will see later, the dissemination is very fast, so we do not expect vehicles entering or leaving the ROI in such a short lapse. The ideal ratio,

Parameter	**Value**
Roadway length	4 km
Sender position	Km. 2
R_{target}	2 km
Traffic densities	{20, 30, 40} vehicles/km
Packet payload	16 B
Simulation runs	1000

Table 4.1: Simulation parameters for the comparison of different basic schemes.

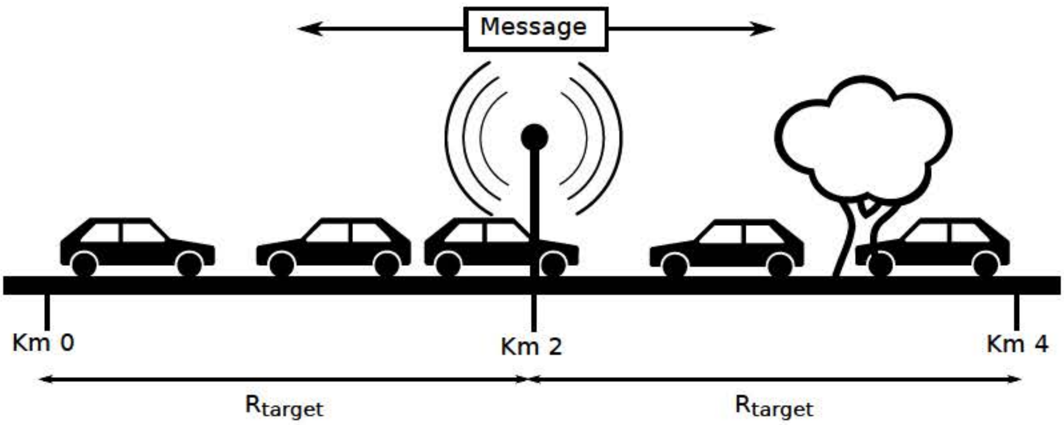


Figure 4.1: Schematic representation of the scenario for the simulations of the basic dissemination schemes.

then, is 1 (every vehicle is reached). Second, the ratio of forwarders per receiver, that we can also see as the number of necessary duplicates per reached vehicle. We want it to be as low as possible. And last, the average end to end delay, which is the mean time it took the message to reach any given node, and that demonstrates how fast the scheme is.

Now we explain the simulation results for each protocol, and then establish a general comparison. All the graphs shown here, and in the rest of the dissertation, show the 95% confidence interval.

Simple Flooding: Contrary to what we might expect, the delivery ratio we see in Figure 4.2 is not the best. This is due to the high number of collisions: it has the maximum ratio of forwarders per receiver, showed in Figure 4.3. In this scheme, every vehicle that receives a message, forwards it. The average end-to-end delay, shown in Figure 4.4, is due solely to the access and propagation delays, as this scheme does not add any latency in the decision process (the decision is always to immediately forward).

Probabilistic Scheme: The results of applying this scheme with different values are in Figure 4.5. The forwarding probability determines the average ratio of forwarders per receiver: we can check it in Figure 4.5(b). The delivery ratio, as we see in Figure 4.5(a), is only acceptable when the traffic density is high, even for the highest probability.

Counter-Based Scheme: As we indicated above, we have used several combinations of threshold (C) and maximum RAD (w) values. The results are in Figure 4.6. This technique tries to estimate how many neighbors may be in the vehicle's area by counting forwarders. This way of operation is able to adapt to the traffic density, as we see confirmed in Figure 4.6(b)—if there are more vehicles, the ratio of forwarders per receiver is lower. In addition, we can check that using a higher threshold, C, lets

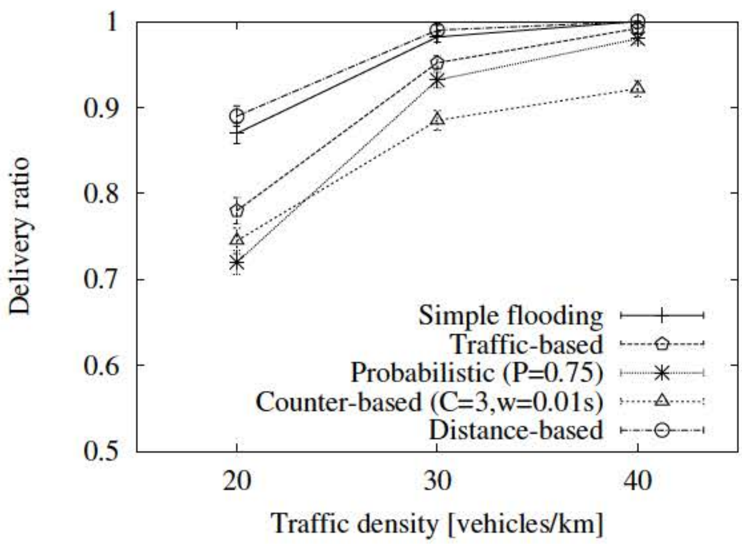


Figure 4.2: Delivery ratio of different basic schemes.

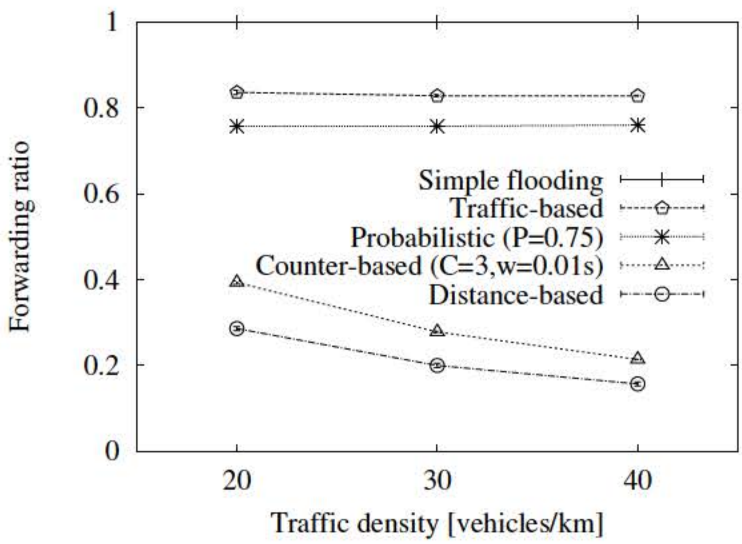


Figure 4.3: Forwarding ratio of different basic schemes.

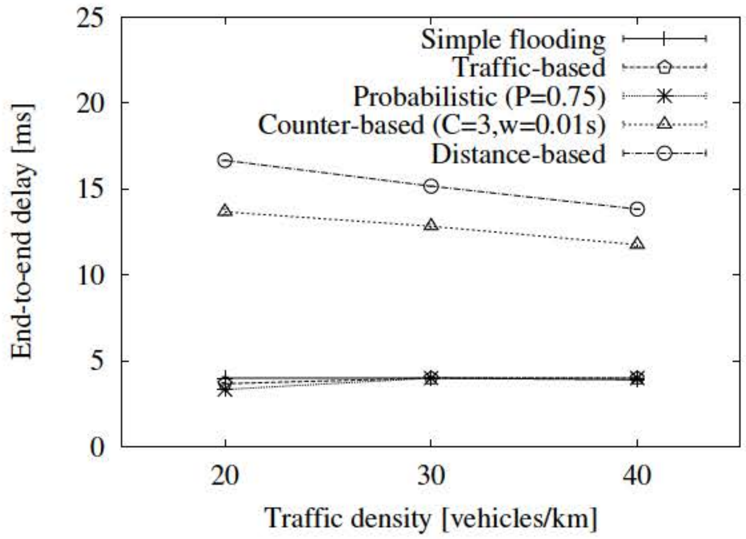
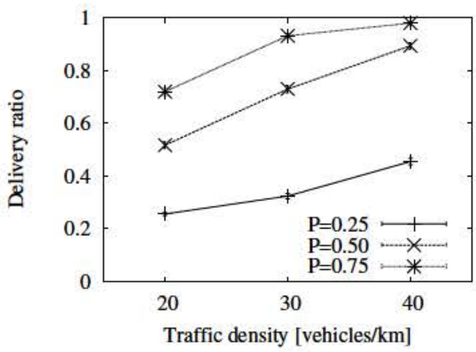
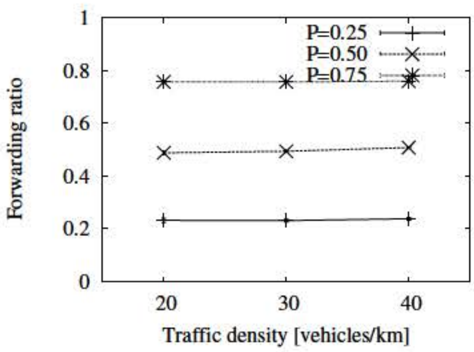


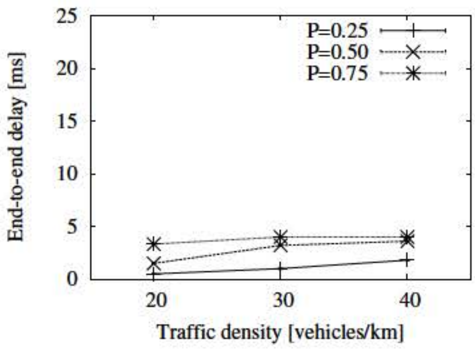
Figure 4.4: Average end-to-end delay of different basic schemes.



(a) Delivery ratio

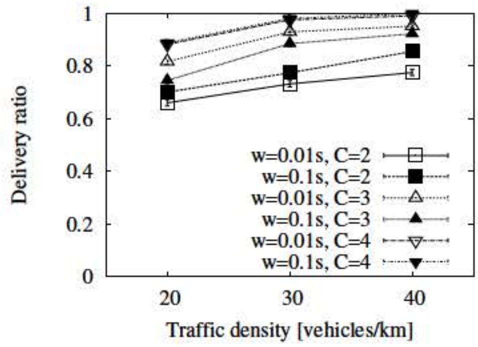


(b) Forwarding ratio

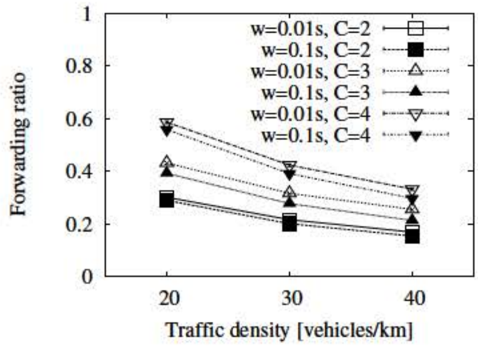


(c) Average end-to-end delay

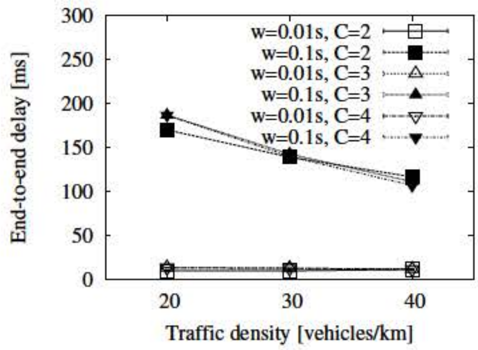
Figure 4.5: Performance evaluation of the probabilistic scheme.



(a) Delivery ratio



(b) Forwarding ratio



(c) Average end-to-end delay

Figure 4.6: Performance evaluation of the counter-based scheme.

a vehicle receive more duplicates and still rebroadcast the message. This leads to a higher number of reached nodes. A potentially shorter RAD, given by the maximum wait, w, reinforces this effect, as it is less likely to reach the threshold if it waits less for duplicates. The main drawback of this technique is the cost in time that the RAD imposes. We show the average time to reach any node in the area, may it be close or distant to the origin, in Figure 4.6(c). There, we can find evidence that the average time is related to the value of w. This effect, however, is highly mitigated in dense networks.

Distance-based Scheme: When using this scheme, the most distant vehicle to the last relay gets the highest priority to forward, by waiting less before doing so. In Figure 4.4, we observe that the resulting end-to-end time, sum of the two waits (W and t_w from Equation 4.1), is relatively high but still reasonable. The movement of a vehicle in that amount of time is negligible, so it will not affect the scheme operation. We can see in Figures 4.2 and 4.3 how they stand out above the rest with regard to the other two metrics.

Traffic-based Scheme: The idea behind this scheme is to select as forwarders those with more chances to find new neighbors—the vehicles traveling at high or low speed. However, this is not likely to happen in such a short time and so, the delivery ratio is high only if the traffic density is high. We can see this in Figure 4.2. Also, in Figure 4.3 we observe a high overhead. This technique might be appropriate in combination with another one, but not applied on its own. In addition, it is to note that a different traffic-based scheme may achieve better results than this one.

In general, we have presented an overview of the different families—simple, traffic-based, probabilistic, counter-based and distance-based flooding. We can see comparative graphs in Figures 4.2, 4.3 and 4.4. For the probabilistic scheme, we have chosen to represent $P = 0.75$ to match the delivery ratio of the others. For the counter-based scheme, we selected $C = 3$ and $w = 0.01$ s as an intermediate configuration of the six simulated ones.

We have found that a probabilistic flooding is unable to adapt to varying densities, so it will work acceptably only under specific conditions. A high probability, P, is necessary for sparse networks but it causes a high overhead in dense ones. A low value will be suitable for dense networks but the dissemination will not work in sparse ones. Despite introducing some knowledge about the environment, our traffic-based scheme on its own is not good enough. However, it could be useful in conjunction with another one.

The two schemes that perform best in terms of overhead are the counter-based and the distance-based. Especially the latter, as it reaches the maximum coverage if the network does not suffer from disconnections. However, the necessary time to collect information during a RAD or to contend makes them slower than the others. For example, in the counter-based scheme, a maximum RAD of 0.1 seconds would be too high if the application needs a quick broadcast. To compensate the reduction of the waiting time, a high value of threshold should be chosen. The distance-based scheme parameters should be tuned properly, too, in order to achieve the optimal performance. There are times in which two or more vehicles that are close to one another rebroadcast the message at the same time. The overhead can be reduced by avoiding these additional retransmissions.

Our conclusion is that the only technique that is able to provide a good delivery ratio and very low overhead amongst those studied here is the distance-based scheme.

The flow diagram of the distance-based scheme that we have created, and that will be the basis of our solutions for vehicular environments, is represented in Figure 4.7. At the moment of receiving any message, a vehicle first checks if it is valid–a message that has expired (its TTL has reached zero) or that has got outside of its ROI must be discarded. Then, if it is new, the vehicle calculates the waiting time, t_w, according to its distance to the previous relay and launches a timer. Else, it may be a duplicate of a message that it is currently holding during its t_w wait. If the TTL of the duplicate is lower than the TTL of the first copy, it means it belongs to a new retransmission. Another vehicle has already taken the role of relay, and so this vehicle must cancel the corresponding timer and abort the retransmission of this message. A second check on the utility of a new retransmission is done–if the new relay is further from the previous one than this vehicle, issuing another duplicate could not help in reaching any more vehicles. Finally, if the timer expires, it means that this vehicle that is the furthest from the last relay and it forwards the message.

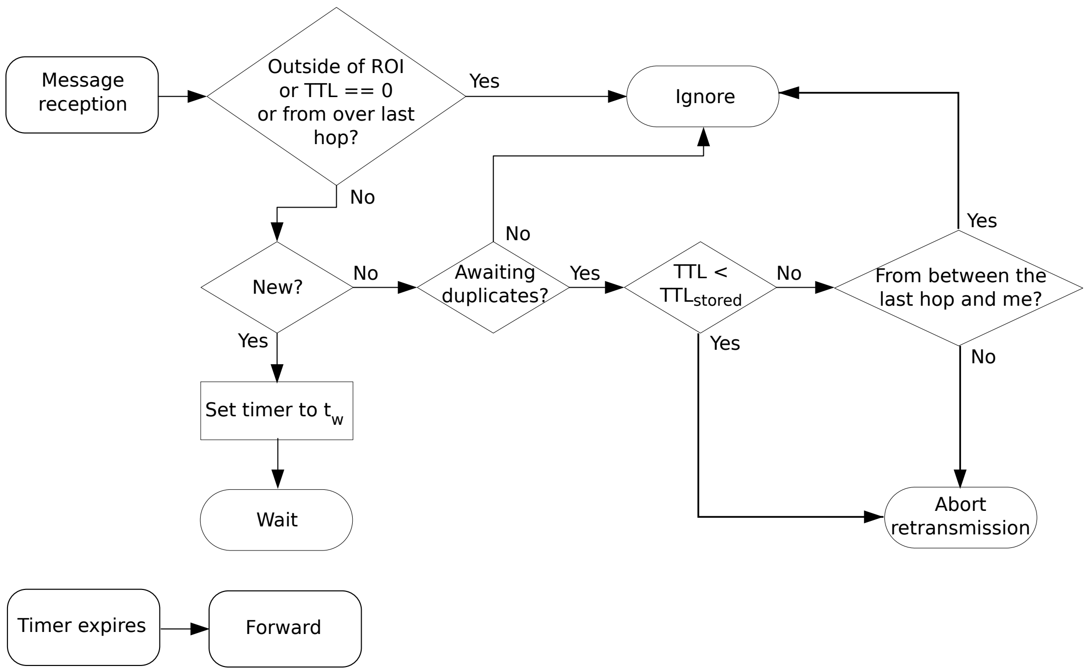


Figure 4.7: Flow diagram of our basic dissemination scheme.

4.3 Conclusions

Our starting point is the typical taxonomy of dissemination schemes in MANETs, that was extended to also include VANET-specific traffic-based techniques in [Chen et al., 2010]. We have chosen or created a scheme for each category: a simple probabilistic forwarding, a typical counter-based scheme, a distance-based implementation that is similar to others existing in the VANET literature, and an original traffic-based algorithm. These schemes, along with a simple flooding for reference, were the base of the study contained in this chapter.

We have simulated all of them in a simple scenario in order to find out which one would be the best basis for our solution. We have paid attention to three different metrics: the delivery ratio, or the portion of receivers achieved, the ratio of forwarders per receiver, that measures the redundancy caused by the scheme, and the average end-to-end delay to each reached vehicle. As we already explained in the Introduction, our priority is to achieve a low ratio of forwarders per receiver and we expected that it would have some cost on any or both of the other two.

The results of our simulations led us to some conclusions. First, we have learned that the inability of the probabilistic scheme to adapt to different traffic densities yields poor results in terms of delivery ratio or redundancy, depending on the situation. Also, that our traffic-based scheme does not have the expected effect because the dissemination takes place in a very short lapse, in which the vehicles are almost static.

The counter-based and the distance-based schemes offered better results because they are able to adapt to different traffic densities. Specifically, the distance-based one showed the best performance in both the ratio of forwarders per receiver and the delivery ratio. In exchange, it is the slowest scheme of the set.

So, in conclusion, the distance-based scheme is the one that best suited our initial requirements and so we choose it for our dissemination solution. In particular, we use Equation 4.1 as our starting point. Next, we will have to adapt and optimize the scheme to each of the VANET scenarios—roadways and urban areas. We start with the former, that we develop in the next chapter.

Chapter 5

Optimizations for Interurban Roadways

In the previous chapter, we studied a selection of different basic dissemination schemes and selected the distance-based dissemination as the basis of our work. The specific implementation is detailed in Section 4.1. This scheme showed the best results in terms of redundancy and delivery ratio, making it the best choice for creating a solution that uses efficiently the available bandwidth.

Now, we set on the task of creating a specific scheme for roadways using it as the initial point. It has two main stages: optimizing the algorithm to the specific scenario, and making it resilient to short-lived disconnections between portions of the vehicular network.

So, in this chapter, we begin by studying the minimum ratio of forwarders per receiver that we can achieve with this scheme. Next, we work on minimizing the per-hop delay that, as we learned in the previous chapter, is the weakness of the distance-based scheme. In both cases, we first reach a conclusion analytically and then we validate our findings with simulations. Then, we describe the design process of a store-carry-forward mechanism that let us achieve the resiliency to network partitions that we need.

We test the resulting scheme under a moderately loaded channel to mimic a real-life setting. We also run DV-CAST in our simulations scenario and compare its results to those of our approach, to assess our contribution to the state-of-the-art.

We end the chapter with a list of different proofs of concept that we have developed during the course of this thesis, often in collaboration with other research groups, followed by our conclusions.

5.1 Ratio of Forwarders per Receiver

Our starting point is the description of the distance-based scheme that we provided in Section 4.1. In particular, in this section we use Equation 4.1 to study the minimum ratio of forwarders per receiver that we can achieve with it. We also need to take into account the particular characteristics of roadway traffic that we commented on Section 3.1.

So, let us assume that the vehicle density is enough, so that there is not any disconnection in the distance of interest, R_{target}. We say that the number of receivers in such a distance is $\rho \times R_{target}$, where ρ is the traffic density in the road segment in vehicles per space unit.

If there is not any collision, only one vehicle from every covered area forwards the message. If the relays were at the edge of each reception range, every new covered area would not overlap with the previous one. In this ideal scenario, there would be one forwarder per the average number of vehicles that fall in a reception range.

$$\frac{1}{\rho r} \tag{5.1}$$

But in reality, forwarding vehicles are typically at a distance before the edge. We call the distance from the relay to the most distant vehicle in its reception range d_{max}.

According to the studies summarized in Section 3.1.3, the distance between consecutive vehicles in non-sparse scenarios can be modeled using a normal distribution with $\mu = 1/\rho$. So d_{max} is determined by the chain of normal inter-vehicle spaces that fit inside the constant reception range, r. Then, the average value, $E[d_{max}]$, will necessarily comply with Equation 5.2:

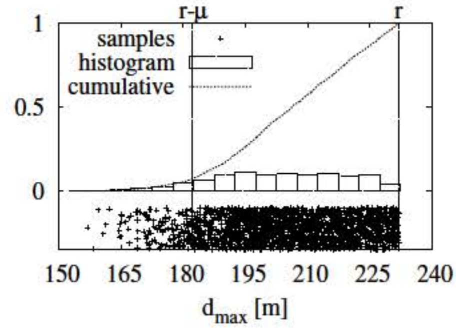
$$r - 1/\rho < E[d_{max}] < r \tag{5.2}$$

In order to better understand the distribution of d_{max}, we have carried out empirical simulations of the vehicles positions along the road. We have used several fixed standard deviations of the inter-vehicle spacing, combined with a long list of different traffic densities. What we have seen is that d_{max} greatly depends on the inter-vehicle variance. We present four representative graphs in Figure 5.1. The left column shows the registered values of d_{max} when we used a high variance to distribute the vehicles along the road–the cumulative line, that gives an estimation of the cumulative distribution function (cdf), indicates an uniform distribution. If we use a smaller variance, as in the right column, the tails of each normal do not overlap anymore. So, though the underlying behavior is not uniform, when considering just the average of d_{max} for any given case, we will have to calculate it as the mean of an uniform distribution in the range $[r -^1 /_\rho, r]$, that is,

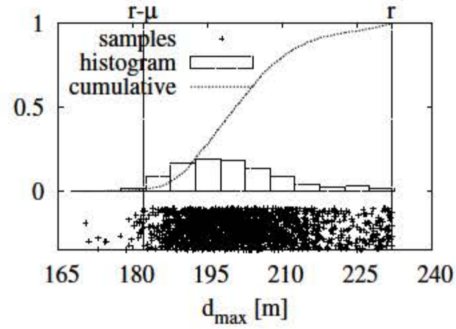
$$E[d_{max}] = r - \frac{1}{2\rho} \tag{5.3}$$

We can see it more clearly in Figure 5.2, where we show the values of $E[d_{max}]$ obtained by simulations, along with the representation of Equation 5.3.

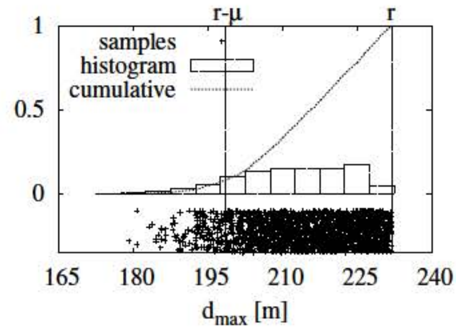
Finally, the total number of vehicles that forward the message in the given distance, R_{target}, will be as many as the covered zones. Therefore, the ratio would



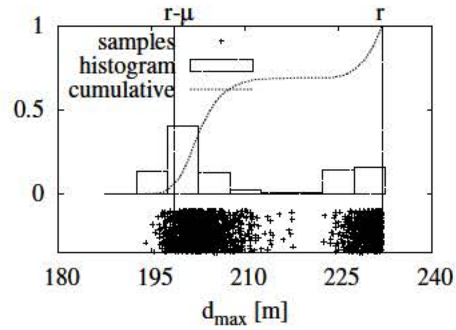
(a) Maximum variance, $\mu = 50\,\mathrm{m}$



(b) Small variance, $\mu = 50\,\mathrm{m}$

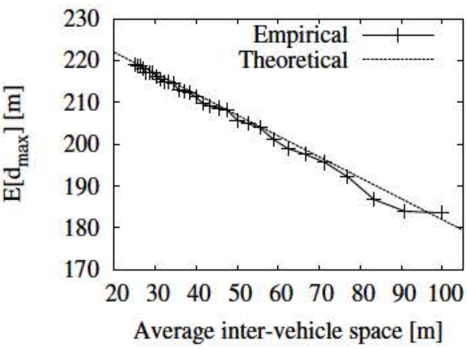


(c) Maximum variance, $\mu = 33.4\,\mathrm{m}$

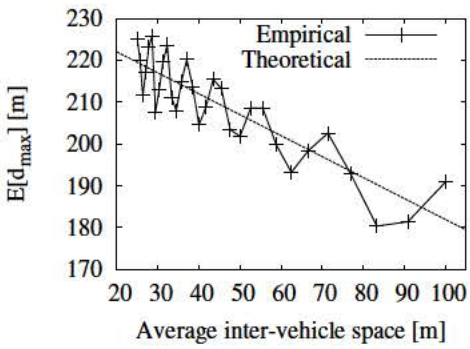


(d) Small variance, $\mu = 33.4\,\mathrm{m}$

Figure 5.1: d_{max} distributions with varying inter-vehicle spacing mean ($\mu = 1/\rho$) and variance.



(a) Maximum variance



(b) Small variance

Figure 5.2: $E[d_{max}]$ in relation to the inter-vehicle spacing mean and variance.

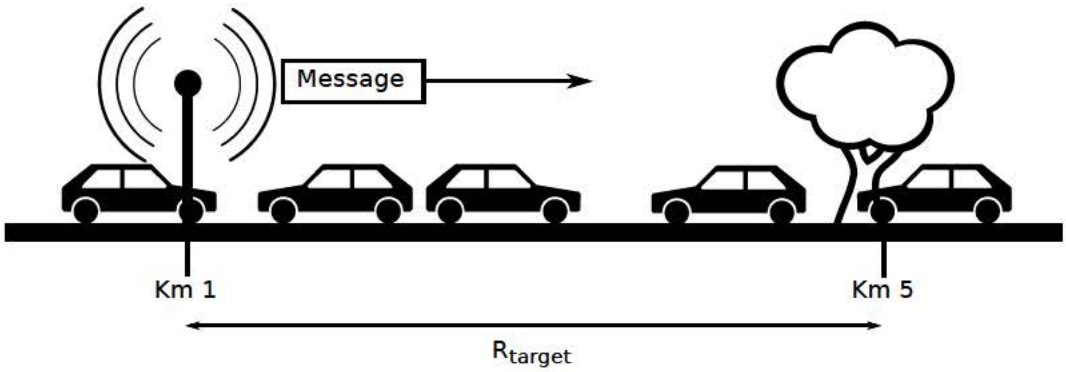


Figure 5.3: Schematic representation of the scenario for the simulations of the distance-based scheme in roadways.

be:

$$\frac{\frac{R_{target}}{E[d_{max}]}}{\rho \times R_{target}} = \frac{1}{\rho\left(r - \frac{1}{2\rho}\right)} = \frac{1}{\rho r - 1/2} \tag{5.4}$$

5.1.1 Validation

We test the base forwarding scheme in a fully connected scenario. We want to check if our assumptions and models are correct in an ideal setting (*i.e.*, with no other ongoing traffic). As we explained in Section 3.2.1, we can assume that for a fully connected network, the global traffic density in a roadway segment is at least of 30 vehicles/km. Therefore, we use a range from 30 to 40 vehicles/km for these simulations. The traffic densities for each direction are symmetric.

We want to use a target area radius, R_{target}, of 4 km. Supposing we have the sender at the center of the ROI, like in our study of basic schemes in Chapter 4, we can simulate just a half of the target area. We show the new setup in Figure 5.3. We rise the packet payload in order to simulate the trasfer of actual content (other works, like [Korkmaz et al., 2007], use a payload of at least 100 Bytes). The summary of the configuration parameters that are specific to this batch of simulations is in Table 5.1.

Parameter	Value
Roadway length	6 km
Sender position	Km. 1
R_{target}	4 km
Traffic densities	{30–40} vehicles/km
Packet payload	216 B
T_{max}	18 ms
W	5 ms
Simulation runs	100

Table 5.1: Simulation parameters for testing the distance-based scheme in roadways.

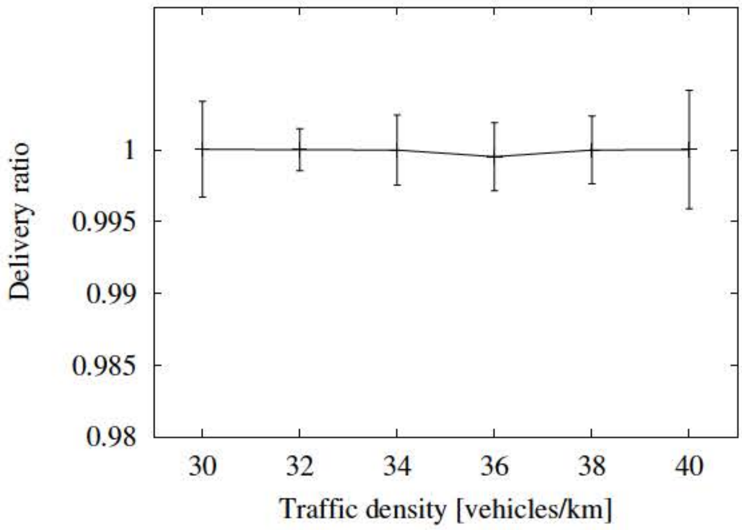


Figure 5.4: Delivery ratio of the distance-based scheme in connected roadway networks.

After running the simulations, the first step is to check if they have reached a 100% coverage. A look at Figure 5.4 confirms that most of the runs conform to this requisite. Let us recall that the equations in this section are only valid in connected networks.

In Figure 5.5 we use dotted lines to represent the theoretical forwarding ratio, calculated with Equation (5.4), and the optimum, as in Equation (5.1). The graph confirms that the simulation results, drawn with error bars, tally with the analytical model. Given that the forwarders are always the closest ones to the edge, the number of overlapping covered areas is minimized. As a result, this scheme gets very close to the minimum number of retransmissions to reach 100% of the vehicles when the roadway network is connected.

5.2 Configuring the Maximum Per-Hop Delay

We have assessed the minimum ratio of forwarders per receiver that we can achieve with our distance-based scheme. We could check in Chapter 4 that the good performance in this sense comes at the cost of a high latency. Now we are going to study the per-hop delay incurred by this scheme. This way, we hope to be able to configure a maximum per-hop delay that will mitigate this effect as much as possible without altering the other performance metrics.

The algorithm's per-hop delay, or the total time that a vehicle waits before forwarding (i.e., we do not account for MAC contention, transmission nor propagation here), is given by Equation (4.1) and the guard time for duplicates:

$$w = W + t_w = W + T_{max}\left(1 - \frac{d_{min}}{r}\right) \tag{5.5}$$

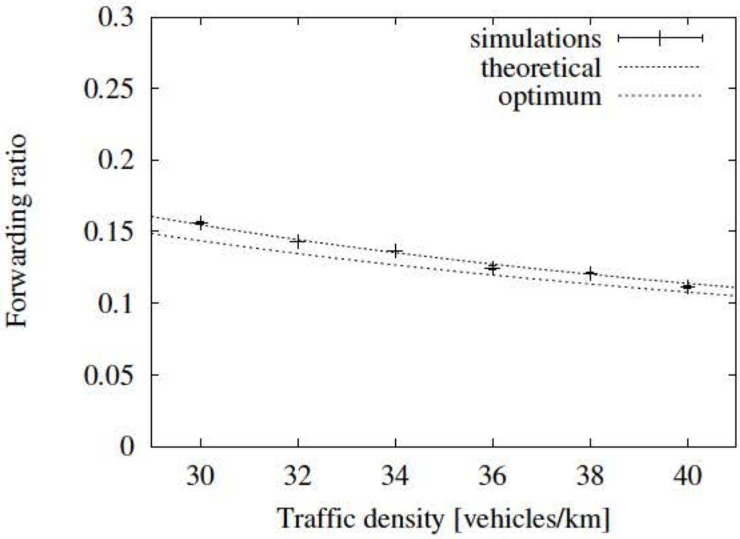


Figure 5.5: Forwarding ratio (i.e. number of forwarders per receiver) of the distance-based scheme in connected roadway networks.

And so, the average per-hop delay is:

$$\bar{w} = W + T_{max}\left(1 - \frac{E[d_{max}]}{r}\right) \tag{5.6}$$

If we substitute the $E[d_{max}]$ with its value as we have learned in the previous section, we have the delay as a function of the density:

$$\bar{w} = W + \frac{T_{max}}{2\rho r} \tag{5.7}$$

We can see that T_{max} plays an important role in the performance of the scheme. The lower this value, the shorter the per-hop delay will be. However, we want to keep it high enough to avoid collisions.

It may happen that two vehicles are located so close that they calculate similar forwarding delays. When their timers expire, they both try to retransmit the message almost simultaneously. The second vehicle is not able to hear the first one's packet before forwarding. We call τ to the minimum difference between their respective forwarding delays (t_{w1} and t_{w2}) so that this does not occur:

$$\begin{aligned} & t_{w2} - t_{w1} < \tau \\ & \rightarrow T_{max}\left(1 - \frac{d_2}{r}\right) - T_{max}\left(1 - \frac{d_1}{r}\right) < \tau \\ & \rightarrow d_1 - d_2 < \frac{r\tau}{T_{max}} \end{aligned} \tag{5.8}$$

If we take $d_1 - d_2$ as the inter-vehicle spacing, that is, $1/\rho$, we have an equation for the lower limit of T_{max}:

$$T_{max} > \rho r \tau \tag{5.9}$$

Now, we want to suggest a valid value for any density, ρ, expected in the road. We may determine the traffic density at road-level but a given vehicle may be experiencing a different density locally. Even more, this same vehicle may experience a very different traffic situation after a few seconds. Therefore, our aim is to suggest a value for T_{max} that would yield good results for any value of ρ.

As the forwarding ratio also depends on the traffic density, we can substitute ρ in Equation (5.4) with $T_{max}/(\tau r)$ from Equation (5.9).

$$ratio = \frac{1}{\frac{T_{max}}{\tau} - \frac{1}{2}} \tag{5.10}$$

τ is constant and so the forwarding ratio is a function of T_{max} in the form, $y = 1/x$. The curve, $1/x$, generates a cone around the axial symmetry axis in $y = x$ with the vertix in $(1, 1)$. Before this point, the function goes down very fast and, from then on, very slowly, being $\lim_{x\to\infty} 1/x = 0$.

The zone of interest in our problem is at the right of the symmetry axis. What is more, we can take this intersection as a reference. From $x = 1$ until $x \to \infty$, the curve goes down from $y = 1$ until $y = 0$. We search, within this zone, the x where the curve reduces its y value by 95%, $y_{5\%}$. that is, $y_{5\%} = 1/x_{5\%} = 0.05 \to x_{5\%} = 1/0.05$.

Our ratio equation can only return values from 1 until 0, too. We just need to solve for T_{max} in Equation 5.10 to get know the minimum admissible value:

$$\frac{1}{\frac{T_{max}}{\tau} - \frac{1}{2}} = 1 \to T_{max} = \frac{3\tau}{2} \tag{5.11}$$

or the value that makes the ratio equals to 0.05 (our $y_{5\%}$):

$$\frac{1}{\frac{T_{max}}{\tau} - \frac{1}{2}} = 0.05 \to T_{max} = \tau\left(\frac{1}{2} + \frac{1}{0.05}\right) = 20.5\tau \tag{5.12}$$

5.2.1 Validation

As a first step, we want to know the value of τ in our simulated environment. For this purpose, we put two fixed nodes together and another one 200 m apart, so that both of them were closer than r to it. The node that is alone sends a message, and the other two try to forward it according to the described scheme. As they are very close, both nodes forward the packet, because none of them can hear the other one's retransmission before trying to access the channel. We slowly move only one of the receivers towards the sender in successive simulations. There is a point in which this node is able to abort its retransmission. The difference between the scheduled forwarding times at this point is τ. We are able to determine that $\tau = 0.914$ ms with an error of one microsecond. Therefore, we configure $T_{max} = 18$ ms.

In addition, we need to find a fitting value for W. We set up a scenario of

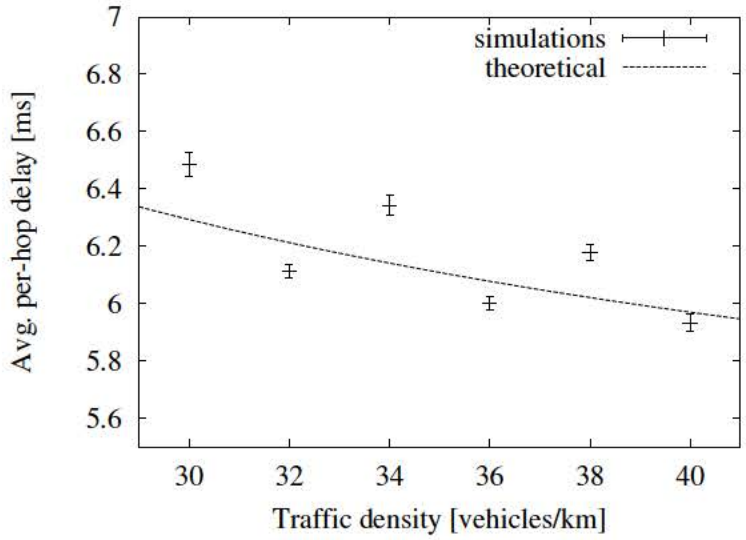


Figure 5.6: Average per-hop delay of the distance-based scheme in connected roadway networks.

4 km with a traffic density of 30 vehicles/km. Every vehicle broadcasts irrelevant packets of 620 bytes to their one-hop neighbors in order to keep the channel loaded to 60%. In this scenario, one of them sends a message that is forwarded by the rest according to the described scheme. In such a congested network, packets collide with a high probability. We have observed the instants when any vehicle receives simultaneous duplicates of the same packet. The difference between the minimum and the maximum times is bounded below 5 ms. And so, we set $W = 5$ ms.

We have tried to configure our simulations as close to reality as possible. However, other circumstances, as a difference in the transmission power, may imply that these values for τ and W do not apply in another scenario. The summary of all the configuration parameters for the simulations is in Table 5.1.

We show the results of our simulations in figures 5.6 and 5.7. Again, we have drawn dotted lines to represent the theoretical average per-hop delay over the simulation results. Figure 5.6 depicts the evolution of the average per-hop delay, $\bar{w}$, in function of the traffic density, ρ, as described by Equation (5.7). It shows the sinuosity that we could already appreciate in Figure 5.2. Figure 5.7 demonstrates the effect of different T_{max} values for a same traffic density. The small vertical shift corresponds to the same sinuosity, as can be seen in the point for $\rho = 40$ vehicles/km in Figure 5.6. Therefore, the results prove the analytical model and the suggested value of $T_{max} = 20.5\tau$ is appropriate for a moving scenario, too. The reason for this is that messages travel much faster than vehicles. Even if the relay had to wait the maximum per-hop time (*i.e.*, $W + T_{max}$, in our scenario about 23 ms), the vehicle would move less than a meter from the reception of the packet to the time of forwarding it. Though in movement, the scenario is almost static from the point of view of communications speeds.

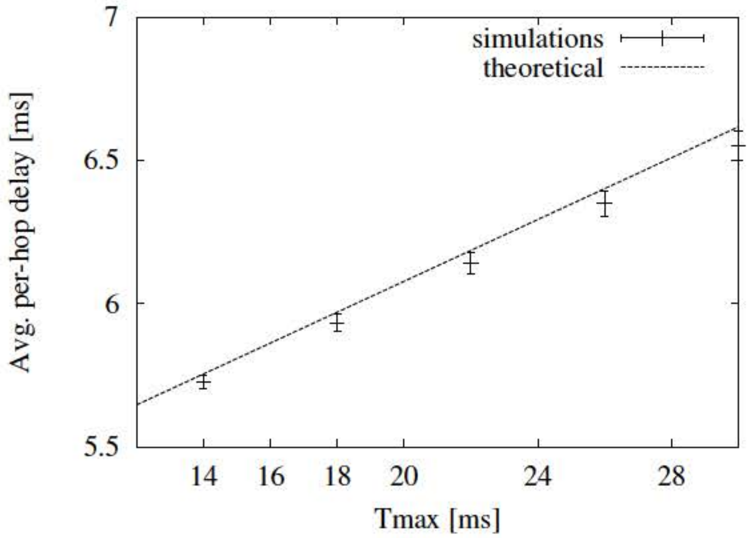


Figure 5.7: Average per-hop delay of the distance-based scheme in a roadway scenario with $\rho = 40$ vehicles/km.

5.3 Resilience to Short Disconnections

When the traffic is sparse (*i.e.*, during non-rush hours) we find gaps between vehicles usually larger than the communication range. The scheme for roadways is not complete until we find a system to overcome this situation and let the message travel through the whole area of interest. Therefore, we have added our own store-carry-forward mechanism, customized to the previously described scheme. The basic idea in store-carry-forward is that, if a relay cannot find another one to forward the message, it stores the message and carries it for some time, until it finds someone who can forward it. Now, we describe a series of measures to implement this idea successfully.

Providing an Acknowledgement System

Every relay needs to learn if it reached new neighbors or if it has to carry the message and forward it again in the future. The easiest way, that avoids putting more packets into the channel, is treating a new retransmission from another vehicle as an implied acknowledgment. If the relay does not hear any other doing so, it means that nobody has become the next relay. Then, it must activate the store-carry-forward mechanism.

Finding the Right Time to Forward Again

Given the case that a vehicle has to store-carry-forward a message, we decided to avoid using *hello* packets to detect new neighbors. We intend to maximize the utility of each retransmission. Instead of forwarding each time that a new neighbor

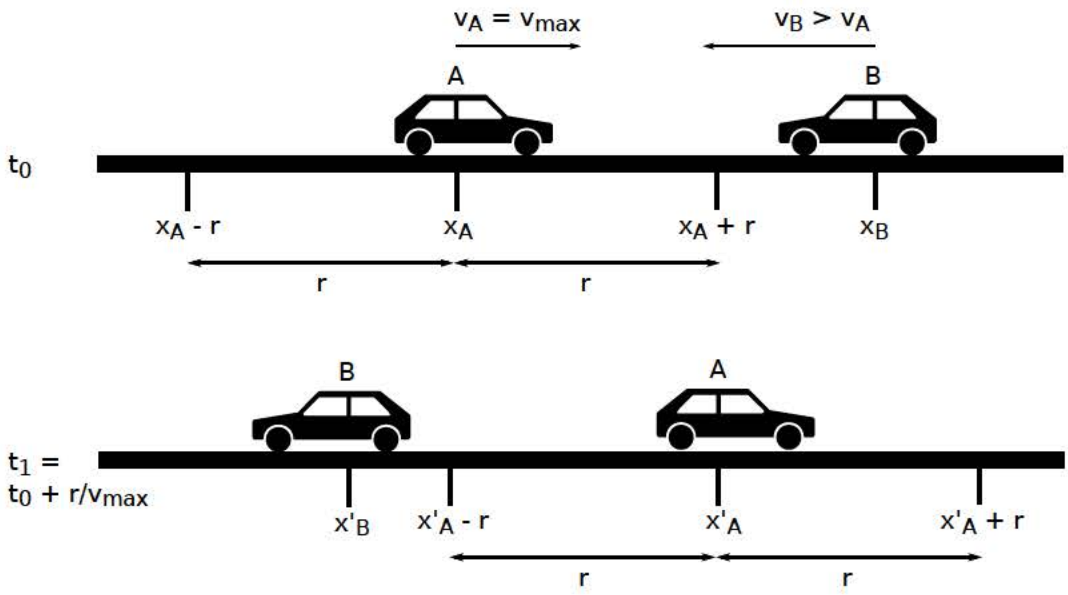


Figure 5.8: Case depiction.

appears, we wait until some may have entered our communication range and before they leave it.

If the frequency of retransmissions is too high, there will be little variation in the scenario, and the probability of finding new neighbors will be low. If the time period is too long, the relay may be missing passing vehicles while it is waiting. Therefore, we have to maximize the probability of finding new neighbors at the time of forwarding.

The chosen time period for this task will be an estimate of how long it will take this vehicle to get out of its currently covered area. That is:

$$r/v_{max} \tag{5.13}$$

We use the legal speed limit, v_{max}, to avoid assumptions about the average speed on this road. If the vehicle is traveling at a lower speed than the limit, it will forward the message again before it has left the last covered area. However, the rest of the vehicles in its own direction, or the vehicles in the opposite direction, may be traveling at a speed closer to the limit, and so, they will not miss the retransmission.

Let us consider the situation represented in Figure 5.8. The relay, denoted by point A, forwards a message at t_0. The vehicle coming in the opposite direction (B) does not hear it, because it is further than r from A. A travels at the speed limit, while B travels at a higher speed. At t_1, when A forwards once more, B will be again further than r, but past the relay this time. This case is possible, but not very probable. Furthermore, the reception of the message is not vital. The information in it is not safety-related, and there are still traffic signs on the roadway. Therefore, we opt to not rise the frequency of retransmissions, at the price of this possibility.

Selecting a Relay

Now, the implied acknowledgments pose a problem: if the new relay gets out of the coverage area of the last one before the retransmission, the latter will not be able to detect it. Then, it will go on forwarding over and over again. As the rest of the vehicles have already heard the message, they will not become a new relay of an old packet. Therefore, it will only stop when it reaches the border of the message target radius.

To avoid this situation, we add a restriction over the group of vehicles in the coverage range of a relay. Any vehicle will be eligible to be the next relay if it is at $x < r - d_{guard}$. This means that we set a guard distance (d_{guard}) to prevent vehicles close to the edge of the coverage range from taking part in the forwarding process. This distance, d_{guard}, is given by the vehicles' direction and speed and a set of times: the maximum time it takes the network to process the packet (collision resolution and propagation); the initial wait, W, of the forwarding scheme; and the maximum wait, T_{max}, given by the distance function. They all account for $\Delta\, t_{max}$.

There are four possible situations:

1. The last relay and the potential new one are traveling in the same direction and in the same direction as the message, too. Their respective current speeds are v_{last} and v_{new}. In the moment of forwarding, t_0, they are apart a distance, d_0. After the maximum time it may take a retransmission by the new one to reach the last one, $\Delta\, t_{max}$, the last relay has traveled a distance, d_{last}, and the potential new relay, a distance d_{new}. They are apart a distance, d_1, depicted in Figure 5.9:

   $$d_1 = d_0 - d_{last} + d_{new} = d_0 + \Delta\, t_{max}(v_{new} - v_{last})$$

   This d_1 must be less than the coverage radius, r. Therefore, if $v_{new} > v_{last}$, we may face a case where d_1 becomes greater than r.

2. The last relay and the potential new one are traveling in the same direction, but in the opposite direction as the message. We can see an illustration of this in Figure 5.10. In this case, the distance, d_1, after $\Delta\, t_{max}$ is:

   $$d_1 = d_0 + d_{last} - d_{new} = d_0 + \Delta\, t_{max}(v_{last} - v_{new})$$

   Now, the problem may appear when $v_{new} < v_{last}$.

3. The last relay and the potential new one are traveling in opposite directions, coming closer. Then, it is impossible that they get out of range of the other. This case is shown in Figure 5.11.

4. The last relay and the potential new one are traveling in opposite directions, getting further. This case is depicted in Figure 5.12. The maximum distance after the new retransmission is:

   $$d_1 = d_0 + d_{last} + d_{new} = d_0 + \Delta\, t_{max}(v_{last} + v_{new})$$

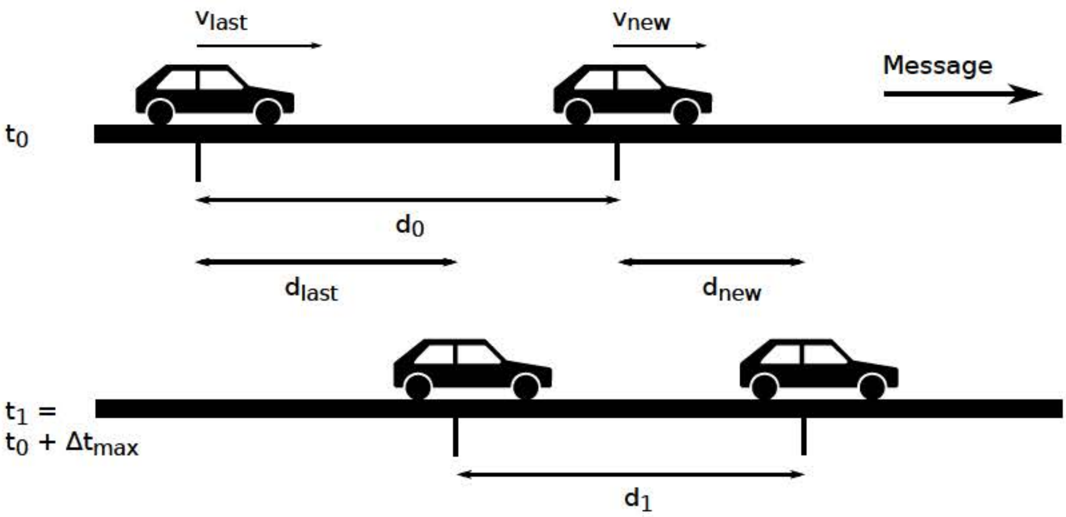


Figure 5.9: Case 1 depiction.

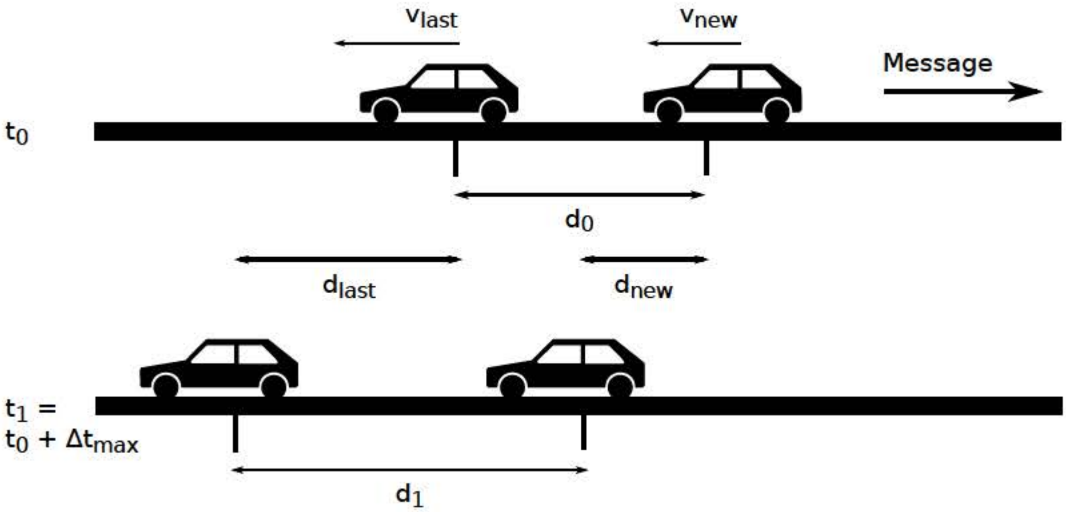


Figure 5.10: Case 2 depiction.

Furthermore, no matter which speed is higher, d_1 may become greater than r.

Because of the forwarding scheme, the location of the last relay must be present in the message. In order to make the new relay able to avoid a problematic case, we are going to include the current speed, too. However, to preserve some of the driver's privacy, we do not want to include whether the vehicle is going towards the sender or away from it. Therefore, the new potential relay will use the most restrictive rule to decide if it is eligible as a relay or not:

$$x < r - \Delta t_{max}(v_{last} + v_{new}) \tag{5.14}$$

If this inequation is true, the vehicle that heard the message will take part in the contention for becoming the new relay. For speeds of 120 km/h, that would mean a reduction of less than 6 m on the coverage radius. This limitation lowers the

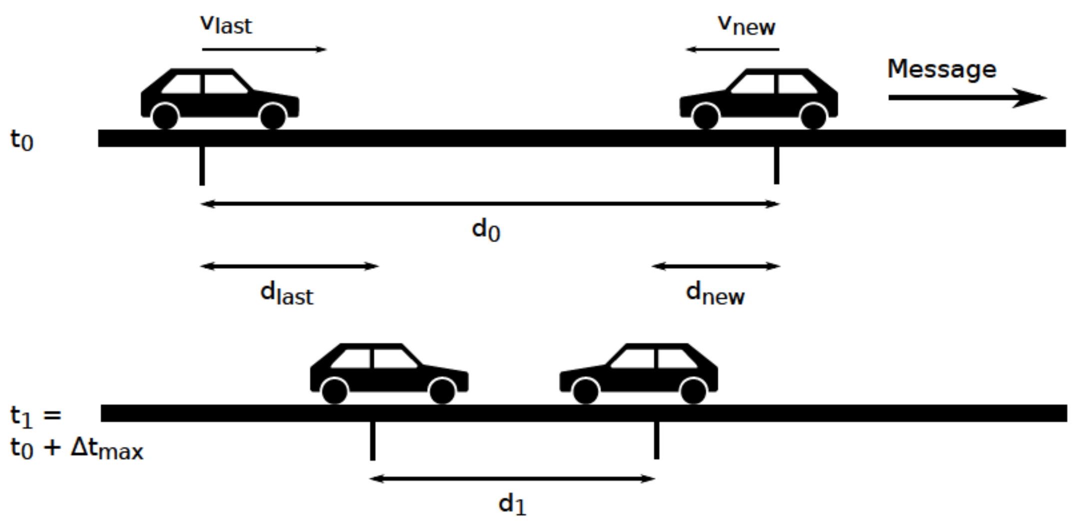


Figure 5.11: Case 3 depiction.

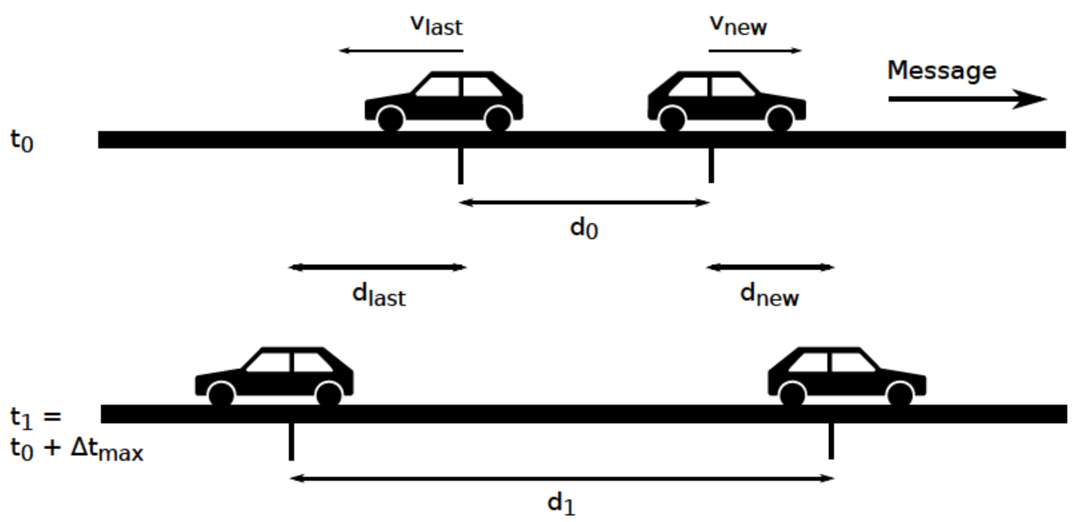


Figure 5.12: Case 4 depiction.

effective vehicle density for forwarding. However, it avoids the wrong activation or the wrong lack of deactivation of the store-carry-forward mechanism, which would cause a high number of unnecessary retransmissions.

Resolution in the Case that More than One Relay is Elected

After forwarding, the relay waits for a new retransmission from someone else before repeating the message itself. If it hears another vehicle doing so, it deactivates the store-carry-forward mechanism. However, we know from Section 5.1 that more than one vehicle may try to forward at almost the same time. After the network processes the collision, all the duplicates reach all the vehicles that forwarded the message simultaneously, because they are a short distance from each other. As every forwarder hears a duplicate of the message after the retransmission, they may all believe that there is a new relay. Maybe, in fact, their duplicates did not reach any other new vehicle, so the dissemination would end there.

We avoid this effect by adding a Time To Live (TTL) field in the message. When a forwarder receives a message with the same TTL, it knows it is a duplicate from a vehicle nearby. It does not mean that there is a new relay.

Now, who must activate store-carry-forward if it is necessary? The answer is, the vehicle that is furthest from the sender, whose location is in the message. Upon every duplicate, every relay can find out if they are more apart from the sender than the issuer of the duplicate.

Carrying the Message Away from the Sender

While the relay is carrying the message, it keeps traveling in its own direction. If it goes in the opposite direction as the message, the latter would travel backwards without any guarantee of getting further thanks to the next relay. Hence, it is not advisable that any vehicle, regardless of its direction, could carry the message.

As we do not make use of beacons, a vehicle does not know beforehand when it will find a sparse network situation. Even in an area with a medium vehicle density, we can find a sparser zone just a few hundred meters ahead; for example, after a way out to an important roadway. It would make sense that only those traveling in the same direction as the message can be the next relay. However, we cannot depend on just the vehicles that travel away from the sender. They could be very few or even nonexistent if the roadway has only one direction.

What we do, then, is to allow vehicles that travel towards the sender to be relays. However, if they have to store, carry and forward the message, vehicles traveling in the opposite direction must help, even if the message is old to them.

Note that all vehicles maintain a duplicate table, so that they do not forward old messages. If a vehicle traveling away from the sender hears a message that a vehicle in the other direction is carrying, it is bound to be old to it, because this vehicle comes from the message's point of origin.

To solve this problem, we set a flag in the message, "Backwards SCF", to indicate whether the relay is doing store-carry-forward (shortened as SCF) "backwards", *i.e.*,

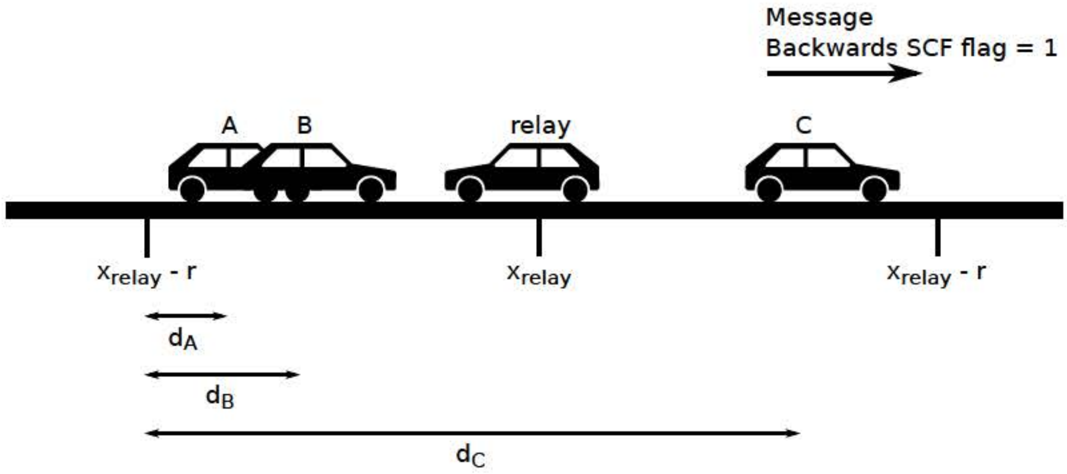


Figure 5.13: Selection of the best "rescuer" in backwards store-carry-forwarding.

in the opposite direction as the message should travel.

If the flag is set to one, a vehicle that travels away from the sender will act as if the message is new to it, even if it is not. It may become the new relay, "rescue" the message and carry it in the right direction again.

Selecting the Best "Rescuer" in Backwards Store-Carry-Forward

When a vehicle hears a message with the backwards flag set to one, it knows it is a special situation. The message cannot travel in the intended direction. In such a case, any vehicle traveling in the same direction as the message must help. It will act as if the message was new, even if it is not. In such a case, this vehicle and other potential "rescuers" can be in any point of the range, $\pm r$, from the relay location, x_{relay}, as depicted in Figure 5.13. Therefore, instead of using Equation (4.1), the "rescuers" will use a variation.

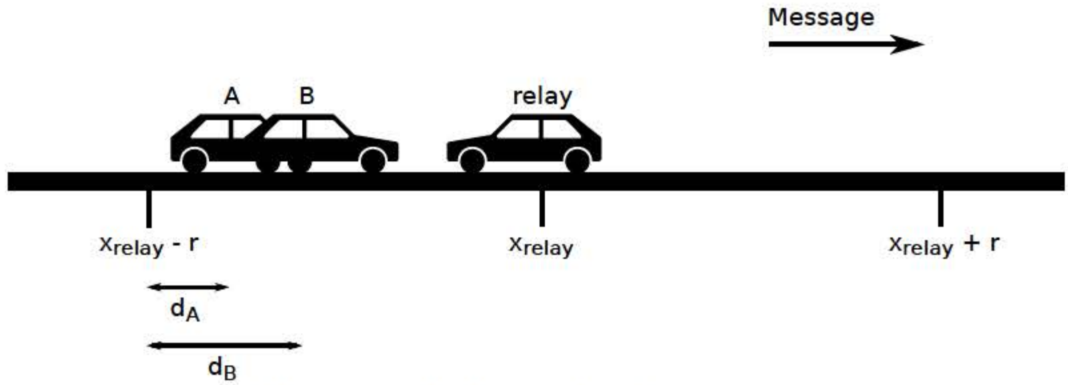
First, they will compute the distance to $x_{relay} - r$ instead of the distance to x_{relay}. Then, they will consider a maximum distance of $2r$ between the closest and the furthest from the origin. The maximum contention time, T_{max}, must always be the same. All this is reflected in Equation (5.15):

$$t'_w = T_{max} \times (1 - d(x, x_{relay} - r)/2r) \tag{5.15}$$

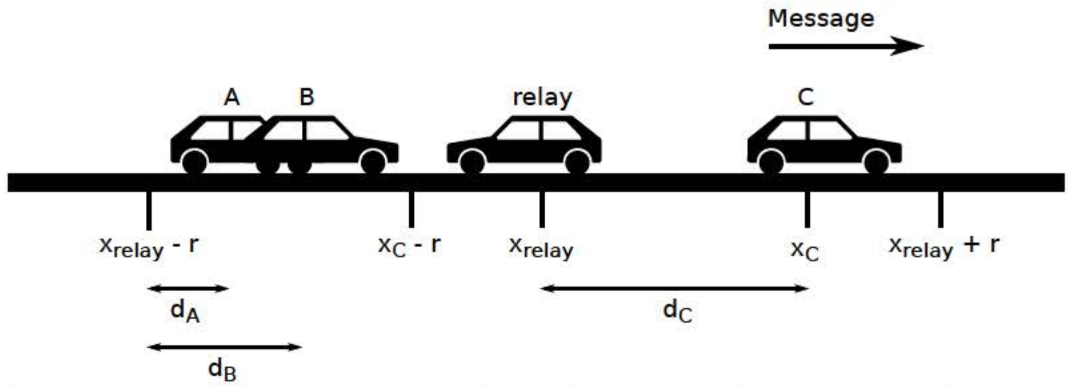
Therefore, this new t'_w will be the time computed for the contention by the potential "rescuers" in the case of backwards store-carry-forward.

Detection of the New Relay by All the Neighbors

When a vehicle is doing store-carry-forward, may it be backwards or onwards, it will eventually find a new set of neighbors. They can be located at any point in the range, $\pm r$, from its location (x_{relay}). Let us depict the case with Figure 5.14(a). Because there is no one in the segment, $(x_{relay}, x_{relay} + r]$, the new relay must be



(a) Equation (5.16) lets us select B as a new relay.



(b) B and C are both selected as new relays. The previous relay must repeat the message from C, so that B can hear it.

Figure 5.14: Relay detection in the range $[x_{relay} - r, x_{relay} + r]$.

chosen from those in the segment, $[x_{relay} - r, x_{relay})$. This would be the one that is closest to the relay, instead of the furthest. That is, if a vehicle hears a new message from a vehicle that is further from the origin than itself, it will still try to forward it, but using this other form of Equation 4.1:

$$t''_w = T_{max} \times (1 - d(x, x_{relay} - r)/r) \tag{5.16}$$

The one who will forward and become the new relay is the vehicle most apart in the direction of the message, $(x_{relay}, x_{relay} + r]$. If there are not any vehicles in that range or if the vehicles in the range $[x_{relay} - r, x_{relay})$ are not able to hear it, they will select a new forwarder among themselves. This situation is depicted in Figure 5.14(a).

The existence of an unnoticed vehicle in the range, $(x_{relay}, x_{relay} + r]$, poses a problem. This case is shown in Figure 5.14(b). Another vehicle from the range, $[x_{relay} - r, x_{relay})$, may be further than r from the new relay. Because it did not hear it, it will forward the message. In addition, it will have to store-carry-forward, because it will not find any other one to become the relay of an old message.

In order to solve this conflict, the last relay will repeat the message as soon as it hears it if the new relay is in $(x_{relay}, x_{relay} + r]$.

As explained in Section 5.3, when a forwarder hears another one retransmitting the message with the same TTL, it compares its distance to the origin with the other's. Now, the forwarder from the range, $[x_{relay} - r, x_{relay})$, will hear the retransmission from the previous relay, located in x_{relay}. Therefore, it will not try to store-carry-forward it.

The new relay in $(x_{relay}, x_{relay} + r]$ will hear, at least, the repetition of its own message by the previous relay. Any duplicate coming from a point closer to the origin must be ignored, then. However, this new relay may be traveling towards the origin and be closer to it when it hears the repeated message. It cannot tell if the message is a repetition of its own one or not, because the packet does not contain any vehicle identifier. Therefore, the new relay will use a margin of $v \times W$ to ignore such a case, where v is its current speed.

Stopping Conditions

Lastly, we need a stop condition for two different situations. One of them occurs when, despite the preventive measures, the next relay travels very fast and the previous one cannot hear the new retransmission. Then, the latter will find itself forwarding forever, because, as noted above, the message is old for the rest of the vehicles. The other situation happens in a roadway with a very low vehicle density. The vehicle cannot find any other one traveling in the same direction for a long time. This would be the case, for example, at 2 am in a weekday. Though increasing the channel load would not be a problem in this case, the message becomes meaningless after the vehicle leaves the target radius.

We will force the vehicle to stop doing store-carry-forward if it gets out of $x_{origin} \pm R_{target}$.

The resulting distance-based scheme for roadways, complete with the store-carry-forward mechanism just described, is represented in Figure 5.15

5.3.1 Performance Evaluation of the Store-Carry-Forward Mechanism

Now we proceed to evaluate the addition of the store-carry-forward algorithm to our dissemination scheme for roadways. We need to ensure there will be enough vehicles moving through it while the store-carry-forward mechanism carries the message towards the end of the ROI, so we add some extra length at each end of scenario (but still simulate only half of the ROI to save computational resources). The total length is 14 km and a static sender is located at Km. 6. We show a schematic representation of the scenario in Figure 5.16.

We test the complete solution against the broadcast suppression forwarding scheme alone (whose flow diagram is represented in Figure 4.7) in sparse scenarios. In this case, we set the density in each traffic direction independently. We fix the density to 5 vehicles/km for one of the traffic directions, while varying the other from 0 vehicles/km (very sparse) to 15 vehicles/km (fully connected). This helps us

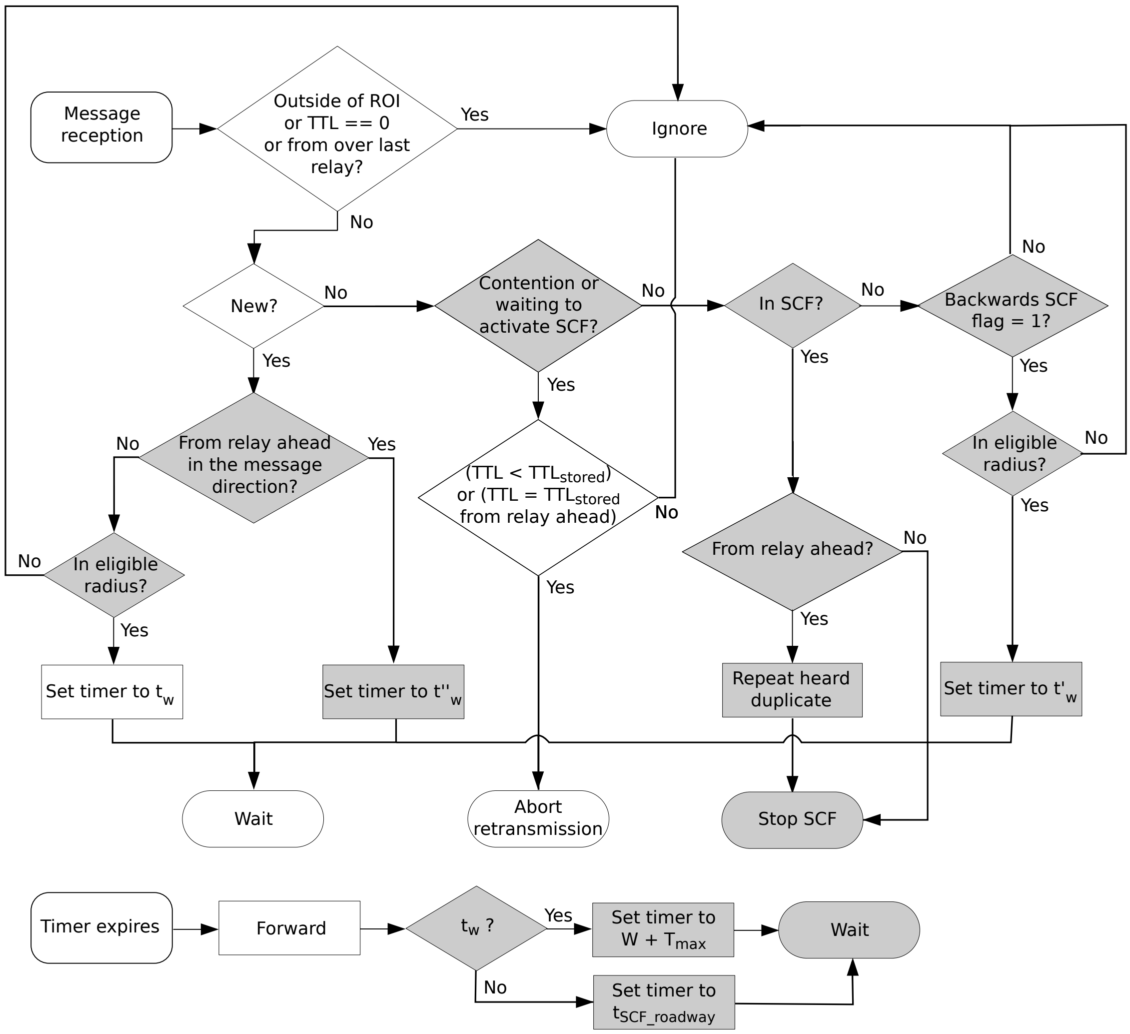


Figure 5.15: Flow diagram of the roadway dissemination scheme. The elements added or modified by the store-carry-forward mechanism are shadowed.

Parameter	Value
Roadway length	14 km
Sender position	Km. 5
R_{target}	4 km
Traffic densities	5 + {0, 5, 10, 15} vehicles/km
Packet payload	216 B
T_{max}	18 ms
W	5 ms
Max. contention and propagation time	28 ms
Δt_{max}	79 ms
Simulation runs	100

Table 5.2: Simulation parameters for testing the store-carry-forward mechanism for roadways.

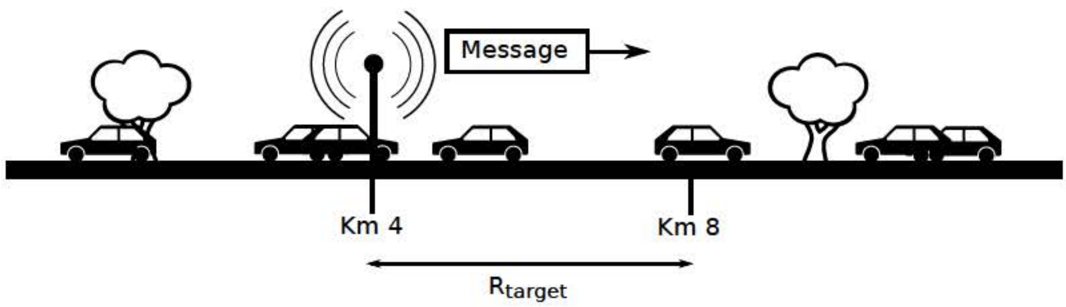


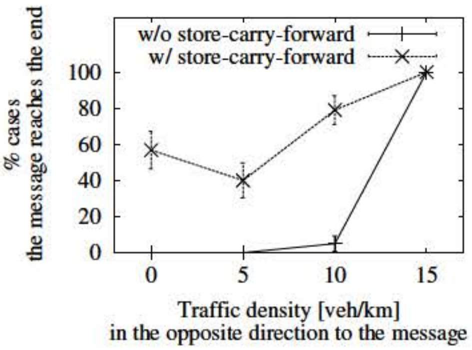
Figure 5.16: Schematic representation of the scenario for the simulations of the roadway scheme with store-carry-forward.

visualize the influence of the population at each side of the road in the performance. The specific parameters for this batch of simulations are summarized in Table 5.2.

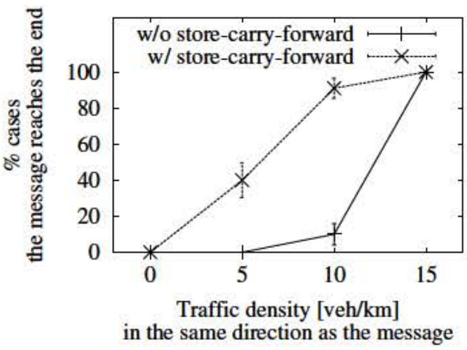
The results of the simulations are compiled in figures 5.17 and 5.18. In the latter, we omit the points for which we could not obtain representative data due to the lack of success in delivering the message. As our sender is located at kilometer 5 in the scenario, and it has set a target radius, R_{target}, of 4 km, the message should reach kilometer 9. In figures 5.17(a) and 5.17(b), we can see the success rate in this task.

The first thing we can notice is that the addition of the store-carry-forward mechanism significantly improves the results for cases of not full connectivity. But, despite its use, the results are still unexceptional when the traffic density on both sides of the road is very low. In particular, it is not possible to cover the region of interest when there is not any vehicle traveling in the same direction as the message. These three aspects are exactly as we expected.

The first two points in Figure 5.17(a) are remarkable. Contrary to the last conclusions, the descending slope is not what we anticipated. We have observed in our traces that the message bounces a lot when the traffic density in both directions is 5 vehicles/km. Of course, if there are only vehicles traveling towards the edge of the ROI, the area is covered sooner or later (as in the first point). But, when the



(a) Fixed traffic density of 5 vehicles/km moving away from the sender.



(b) Fixed traffic density of 5 vehicles/km coming to the sender.

Figure 5.17: Success rate of the solution under ideal conditions and realistic background traffic. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.

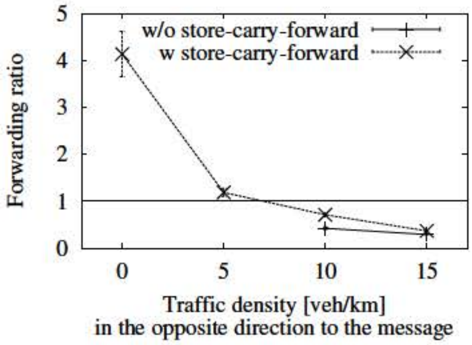
vehicles traveling towards the source are used for store-carry-forwarding frequently, there are times when the message reaches back the origin (as in the second point).

It is worth remembering that the dissemination would be impossible in disconnected one-way roads if vehicles traveling towards the source do not take part as relays. We can check that a traffic density of 5 vehicles/km in the direction of the message in a one-way road achieves almost a 60% success rate (first point in Figure 5.17(a)). However, the same setting in the opposite direction is never enough to get to cover the area (first point in Figure 5.17(b)). Another undesirable effect would be the creation of more and bigger gaps between connected groups of vehicles.

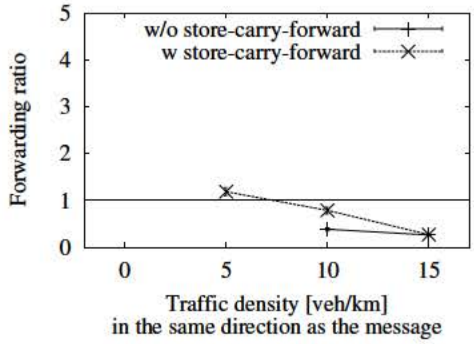
Now, the general improvement in the success rate that store-carry-forward provides, comes at the price of a higher number of messages. In figures 5.18(a) and 5.18(b), we can see the number of duplicates by the number of vehicles that heard the message. In the cases of extremely low density, this ratio is even greater than one (there are more retransmissions than receivers, worse than simple flooding in Section 4.2). This is not a problem, though, because the total number of messages is still low to moderate, as we see in figures 5.18(c) and 5.18(d). There is a distinct peak of duplicates where the traffic is dense but not so much that store-carry-forward is never needed.

5.4 Performance Evaluation

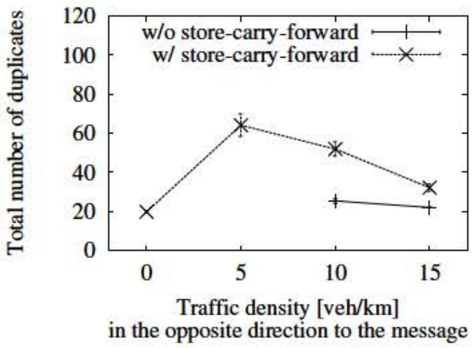
So far, we have worked on several areas of the scheme to make the distance-based dissemination suitable for the roadway scenario—from understanding the ratio of forwarders per receiver and minimizing the latency, to adding a specific store-carry-forward mechanism. Now, we are going to study the performance of the resulting scheme under non-ideal channel conditions and in comparison with a well-known solution as DV-CAST.



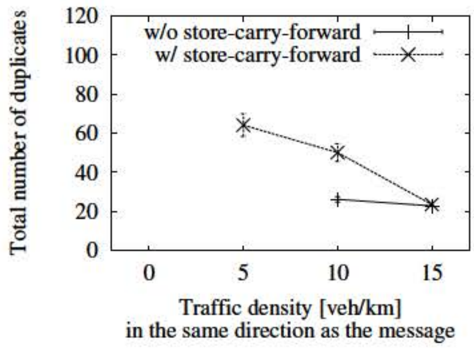
(a) Fixed traffic density of 5 vehicles/km moving away from the sender



(b) Fixed traffic density of 5 vehicles/km coming to the sender

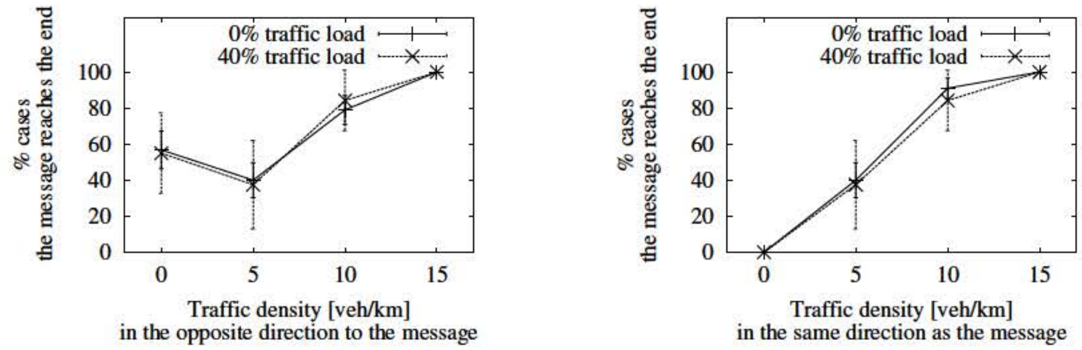


(c) Fixed traffic density of 5 vehicles/km moving away from the sender



(d) Fixed traffic density of 5 vehicles/km coming to the sender

Figure 5.18: Overhead of our approach with and without store-carry-forward in a 4 km ROI radius. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.



(a) Fixed traffic density of 5 vehicles/km moving away from the sender

(b) Fixed traffic density of 5 vehicles/km coming to the sender

Figure 5.19: Success rate of the solution under ideal conditions and realistic background traffic. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.

5.4.1 Performance under Background Traffic

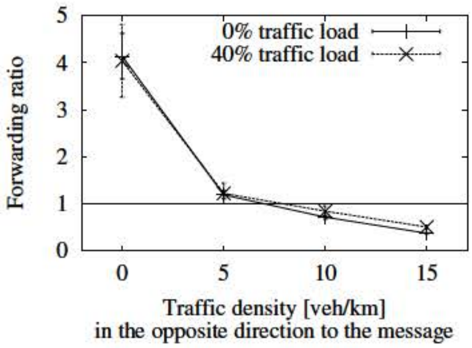
We run a set of simulations to test the solution in a more realistic scenario, where there is background traffic going on the channel. There will be more occasions for access contention and we will probably see an increase in latency and in retransmissions.

The configuration is the same as in Section 5.3.1, but now, we add a channel load of 40% for a normal situation, according to [Brakemeier, 2009]. This channel load is assumed to be due to any type of communication that is already being carried out by all the vehicles in the scenario. Again, we have kept the traffic density in the direction coming to the sender fixed at five vehicles/km, while varying the other direction's. However, we had to reduce the number of repetitions to 20, as the added traffic caused highly time-consuming runs.

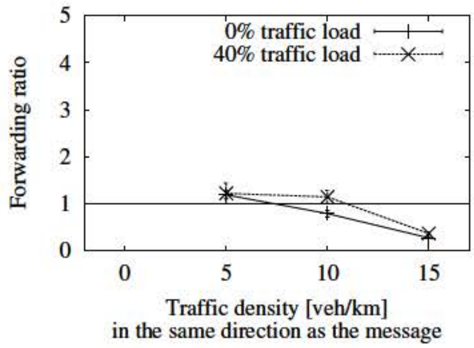
Figure 5.19 shows the success rates in both cases. The results are very similar, denoting that the scheme does not lose effectiveness in non-ideal conditions.

Regarding the efficiency, we can see in Figure 5.20 that a moderate traffic density does affect the performance. The maximum deterioration occurs when the network is not totally connected but almost. In such a situation, part of the vehicles need to apply store-carry-forward (hence increasing the number of retransmissions) and they all are also contributing to the background channel load. These conditions lead to loses due to congestion and the subsequent additional retransmissions.

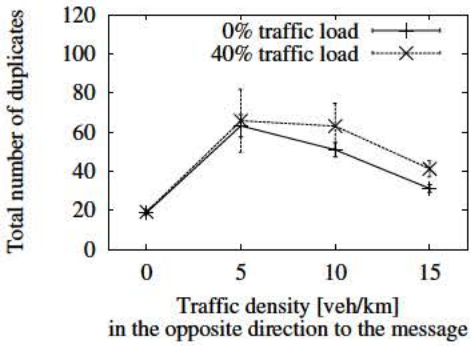
This also affects the latency of the scheme. Figure 5.21 represents the time since the sender emits the message until it reaches the end of the ROI area. The delays are generally the same as those we observed in ideal conditions, except in the case explained above.



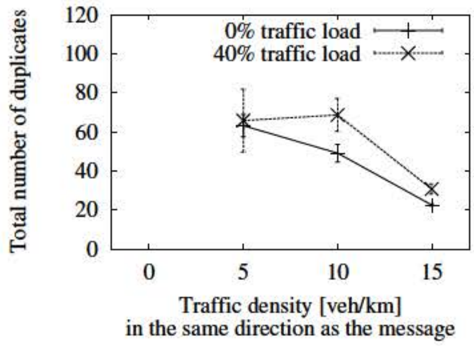
(a) Fixed traffic density of 5 vehicles/km moving away from the sender



(b) Fixed traffic density of 5 vehicles/km coming to the sender

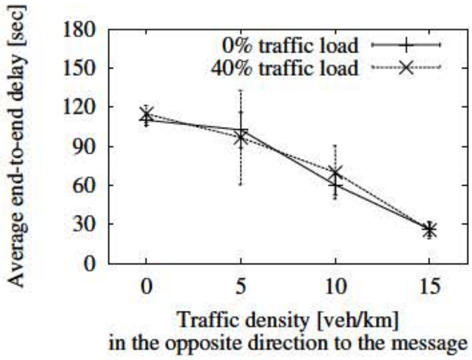


(c) Fixed traffic density of 5 vehicles/km moving away from the sender

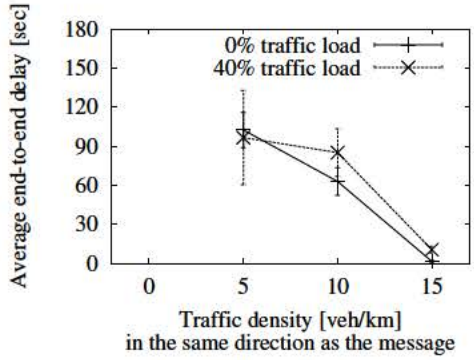


(d) Fixed traffic density of 5 vehicles/km coming to the sender

Figure 5.20: Overhead under ideal conditions and realistic background traffic. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.



(a) Fixed traffic density of 5 vehicles/km moving away from the sender

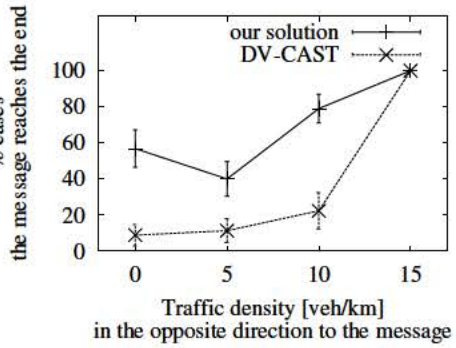


(b) Fixed traffic density of 5 vehicles/km coming to the sender

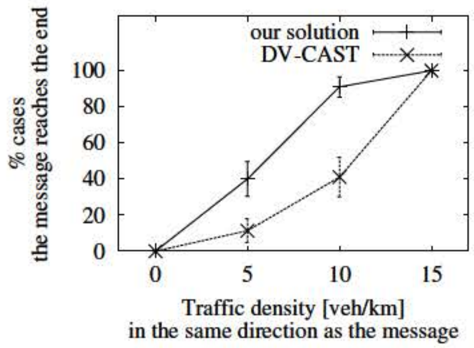
Figure 5.21: Average forwarding delay under ideal conditions and realistic background traffic. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.

Parameter	Value
Hello frequency	1 Hz
Hello packet size	61 bytes
Data packet size	244 bytes
Maximum neighbor table size	5
Packet Timer	2 min
Broadcast suppression	Slotted 1-persistence
N_S	3 slots
$\tau_{DV-CAST}$	2 ms

Table 5.3: Simulation parameters for testing DV-CAST.



(a) Fixed traffic density of 5 vehicles/km moving away from the sender



(b) Fixed traffic density of 5 vehicles/km coming to the sender

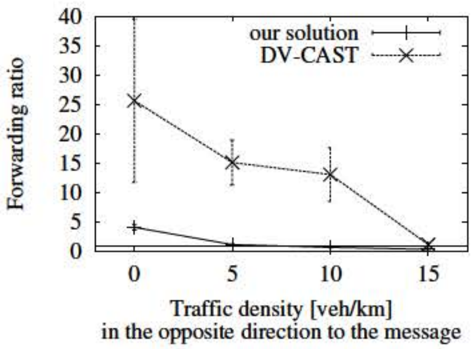
Figure 5.22: Success rate of both solutions under ideal conditions. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.

5.4.2 Comparison with DV-CAST

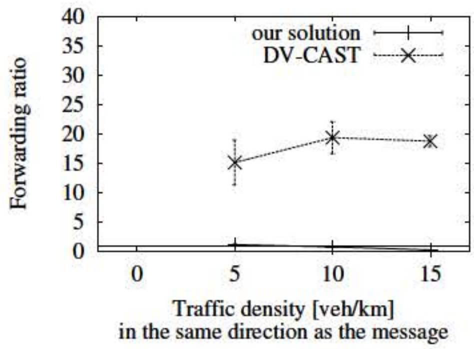
We want to compare our solution with DV-CAST [Tonguz et al., 2010] as a state-of-the-art solution. As we explained in Section 2.2.2, DV-CAST is a vehicular multi-hop broadcast for roadway environments, too. It implements its own store-carry-forward mechanism and can support distance-based flooding. The most obvious difference with our proposal is the use of periodic beacons to allow a general knowledge of the one-hop neighborhood.

Along with the simulations in the previous section, we have run our implementation of DV-CAST in the same scenario. We have configured it as close to the description in [Tonguz et al., 2010] as possible. Only the propagation model (Rician fading) and the MAC protocol (802.11a) used in that work are different from ours (Nakagami and 802.11p, respectively). We have assigned reasonable values to parameters that were not explicitly claimed. We have used the same packet size as in our solution, though the headers are different, to make them as similar as possible. The complete set of values is shown in Table 5.3.

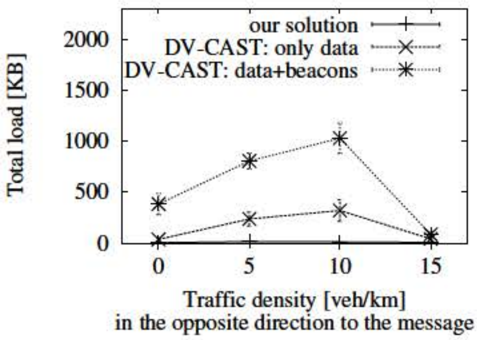
First, in Figure 5.22, we show the success rate when trying to disseminate the



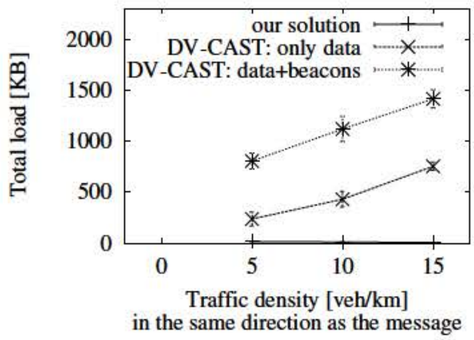
(a) Fixed traffic density of 5 vehicles/km moving away from the sender



(b) Fixed traffic density of 5 vehicles/km coming to the sender

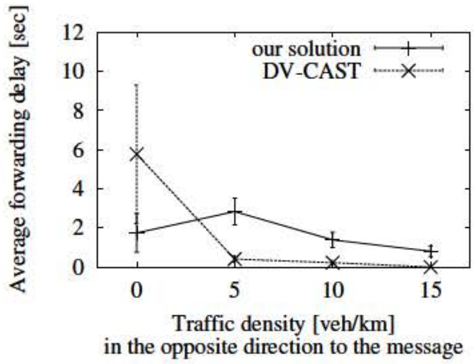


(c) Fixed traffic density of 5 vehicles/km moving away from the sender

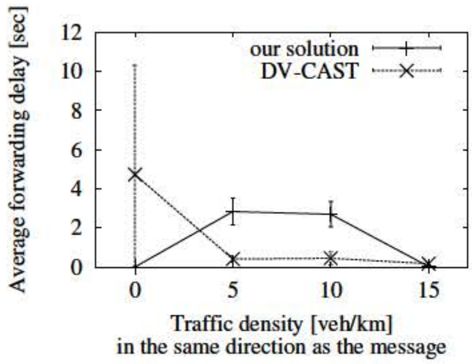


(d) Fixed traffic density of 5 vehicles/km coming to the sender

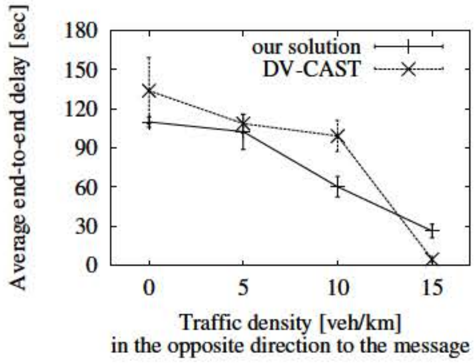
Figure 5.23: Overhead of both solutions under ideal conditions. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.



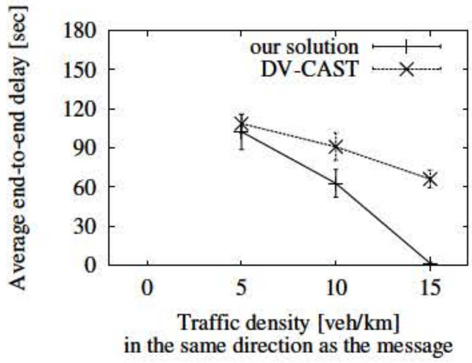
(a) Fixed traffic density of 5 vehicles/km moving away from the sender



(b) Fixed traffic density of 5 vehicles/km coming to the sender



(c) Fixed traffic density of 5 vehicles/km moving away from the sender



(d) Fixed traffic density of 5 vehicles/km coming to the sender

Figure 5.24: Comparsion of different delays under ideal conditions. Density traffic varies in one direction, while the other direction has a fixed density of five vehicles/km.

message through the whole region of interest. DV-CAST achieves a lower rate, because its control over the existence of a new relay at each hop is minimum. In general, it relies on the information about one-hop neighbors and just expects that the message reached a vehicle that can forward it further. The authors of [Ros et al., 2012] agree in this conclusion.

Now, if we pay attention to figures 5.23 (a,b), we can observe the number of sent packets by the number of receivers. Let us recall that the rate of simple flooding (without store-carry-forward or any similar mechanism) is one. When assessing our proposal, we saw this happen when the overall traffic density was very low, as relays had to retransmit the same message several times. With DV-CAST, we see that a value significantly greater than one is the general case. One reason for this is the slotted function to determine the next relay: more than one vehicle are likely to concur in the same time slot. By using a continuous time function, our proposal reduces the probability of this situation. As the traffic density increases, the ratio evolves differently, depending on the sparse traffic direction. This is a consequence of the different assignation of flags that determine the vehicle's situation (MCD, OCD and DFlg, see Section 2.2.2) and its corresponding behavior. In Figure 5.23(a), there are incrementally more vehicles that apply the broadcast suppression scheme instead of store-carry-forward, as they are the ones traveling towards the source and sending the message backwards. In Figure 5.23(a), the number of these vehicles remains low (5 vehicles/km), and the increase in density is for the vehicles that travel in the same direction as the message, who are in charge of carrying the message and forwarding it each time they discover a vehicle in the opposite direction. Apart from this, the use of *hello* packets (or beacons) adds a significant load, as we can see in figures 5.23 (c,d). The amount represented here corresponds to the lapse until the ROI is completely covered: the longer it takes, the more *hello* packets we need to count.

Finally, we can see the latency-related indicators in Figure 5.24. Figures 5.24 (a,b) represent the average delay before forwarding at each hop. Each vehicle has to decide whether to forward an incoming packet or not. In our proposal, this decision is based on the use of several timers, that adds a delay. DV-CAST has a simpler approach, where a timer is needed only in the case of a well-connected scenario. Because of the reasoning above, the wait is short in DV-CAST, too. Thanks to this, the experienced delay is much lower than in our approach in sparse scenarios. In spite of this, the time since the emission of the message until it reaches the end of the ROI is generally longer for DV-CAST, as we can check in figures 5.24 (c,d). This is a consequence of the behaviour observed in figures 5.23 (a,b).

5.5 Proofs of Concept

As we explained in the section about the motivation for this dissertation, the dissemination is a necessary tool for many different applications in VANETs. We have developed three use cases, most of them in collaboration with other research groups. In this section we present them: a service advertising solution, a traffic information service and a solution for preventing collisions.

5.5.1 Service Advertising

There are two types of service discovery. In the "push" mode, the service providers send their information to everyone. In the "pull" mode, it is the node interested in a service that looks for a provider. In a broadcast environment, such as a VANET, it makes sense to use the "push" mode to advertise gas stations (or any other generally interesting roadside service).

We have designed a "push" service discovery system that lets gas stations advertise their location in a wide enough radius. This way, we make this information available to all the vehicles in the area, and they can use it for planning the best next stop. It would run as a UDP application in the vehicle's on-board computer and in roadside units owned by gas stations. We assume that both are equipped with IEEE 802.11p and GPS capabilities. The on-board computer will select from the incoming advertisements only the ones that fit the planned route best and present a sorted list to the driver according to her preferences (price, affiliation, *etc.*).

Their antennae have a coverage range of radius, r, which is expected to be of just a few hundred meters (200–500 m). Therefore, when the gas station sends a message, it reaches only those vehicles that are closest to it. An efficient flooding scheme is a key feature for a service like this. We make use of our dissemination solution in order to reach this goal.

The vehicles that receive the advertisement from the gas station RSU are responsible for forwarding the message to the next group in each direction. The message must be disseminated until it has reached the edge of the target area and about every vehicle in it has heard it. A visual representation is in Figure 5.25.

Gas stations advertise their location and other data periodically. The spread message contains the gas station location and a target zone. In addition to such basic information, the gas station can also insert other data in the message, such as the brand name, prices, special deals, *etc.* The location could be manually configured by the manager if it cannot be obtained automatically by a GPS device. The target zone is determined by a radius of interest, R_{target}. This and the time interval between announcements are both configurable. The manager of the gas station is supposed to have a PC or mobile application that lets her adjust the settings and transfer them to the RSU.

This solution is explained in detail in our articles [Garcia-Lozano et al., 2012b] and [Garcia-Lozano et al., 2013a].

5.5.2 Traffic Information Service

Network connectivity in roadways will help greatly in retrieving a very interesting piece of information when traveling by car—the status of traffic ahead.

A traditional traffic information service is already available in many roadways along the world. It is based on so-called "probe cars" that travel along the road collecting traffic variables. The collected data is transferred to a central processing

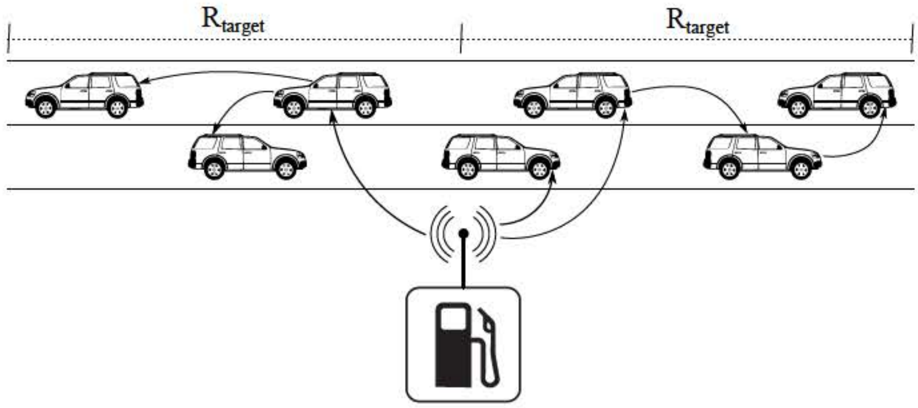


Figure 5.25: Scenario representation for the gas station advertising application.

station. The processed information is then made available to drivers, typically by means of a FM radio channel that they can tune in the vehicle's radio receiver. This system presents a single-point-of-failure problem and may even be easily attacked [Barisani and Daniele, 2007].

With the appearance of inter-vehicular wireless communications, researchers have designed new ways to obtain accurate traffic information in a distributed manner. During the last ten years, interesting 802.11p-based solutions have appeared, some of them very well-known nowadays [Seredynski and Bouvry, 2011].

A main characteristic that all the infrastructure-less solutions share is the traffic information collection model. The vehicles broadcast—"push"—the information to the rest. This incurs in a constant channel load, especially if the broadcasts are periodic. We, on the contrary, propose a change in the model. The interested user asks—"pulls"—for the information she needs only in the moment she wants to know it. This is an important switch because it will allow a significant reduction in the data consumption and the device's computational capacity usage. Another important difference with the previous literature is related to the data aggregation. This becomes less important because the network can afford some more load in a given moment. The lack of aggregation in our solution helps avoiding single points of failure, because the loss of an answer does not mean the loss of much information.

When a driver wants to know the status of traffic at a certain point ahead in her route, she runs our application, named TrafficPoll, in the vehicle's on-board computer. She can choose the point of interest—somewhere at a custom distance or the segment before the next entrance or exit ramp from/to an important roadway. The device finds out the coordinates to which the request packet must travel, and sends it via 802.11p. This request is transmitted with the collaboration of the other vehicles in the roadway, which perform a multi-hop broadcast towards the destination point.

If a device that is running the application in background mode receives a new request, it looks at the source and destination fields of the message (explained later). If it is in the route between these two points, it forwards the packet. Otherwise, it is ignored.

In addition, if the vehicle is within a distance, d, to the target point, it becomes eligible to send back a response. The only information that it must include in it is its own speed. This piece of information, along with the number of replies, is enough for the requester to get a good estimation of the status of traffic in that area. Just knowing just the average speed, as well as the speed limits, is enough to determine the traffic conditions in a segment. The relationship between speed and traffic density was already noted by Williams [Williams, 1997], as well as in more recent works such as [Gramaglia, 2012]. This fact allows the service to work properly even with a low penetration rate.

The responses travel back to the coordinates from which the request came from, so that the user who issued it will receive them. Again, all the consumer devices between these two points collaborate in the process by performing the chose multi-hop broadcast. In exchange, they get information about the traffic status at the given point. This information can be kept so that they do no need to issue a new request if a driver needs to know it in a short time from the previous one. The requester's device calculates the average speed of the repliers and estimates the traffic density from the number of responses. Then, the results are shown to the user.

One of our main goals when designing this service is to keep the usage of the limited, shared bandwidth to a minimum. This is an important aspect because when every vehicle in a roadway is communicating via 802.11p, the available bandwidth becomes a scarce resource. We implement two mechanisms to achieve this goal. The first one is making use of our efficient multi-hop broadcast. The other one is making an important reduction in the number of replies, while keeping the quality of the requester's estimations.

We develop more this idea in the article [Garcia-Lozano et al., 2014b], product of a research stay at the Technische Universitaet Muenchen in Germany.

5.5.3 Ambient Data Gathering

In the context of a joint project with the Unversitat Politecnica de Catalunya, we had the opportunity to collaborate on a solution for preventing accidents in smart roadways. Its starting point is a previous work focused in an urban scenario [Tripp-Barba et al., 2012], and we helped to extend the idea to interurban roadways.

In this solution, road-side units are in charge of collecting information about traffic density and weather conditions. This information is gathered from passing vehicles as well as from weather sensors set on themselves. RSUs share this information among themselves through a sub-network they constitute. After the raw data is processed, the RSUs share the results with the vehicles.

Unlike in a city, where traffic lights are expected to be frequent, in a roadway we cannot assume the same about RSUs. Due to cost issues, it is still unclear where they will be and who will deploy them. So, vehicles will help in the dissemination of the information wherever RSUs are missing. There will be messages of two different priorities. Messages containing sensed or processed information about weather and traffic status (low priority) will travel in a bandwidth-efficient way, while warnings of danger (high priority) will be disseminated fast and reliably.

As we have summarized just above, this service is composed of three steps:

Step 1: Collection of sensed environmental data We assume that in the near future, most vehicles will be equipped with sensors able to determine weather conditions (humidity, temperature, etc.). In addition, they have access to GPS positioning and communication capabilities through the IEEE 802.11p standard. This way, we can make them take part in participatory sensing as explained by [Mendez et al., 2011]. Participatory sensing alleviates the costs of installing a few expensive, complex sensing units, and provides a better map of the whole area. Vehicles send short status messages to the nearest RSU ahead. This way, we avoid redundancy in the network and each RSU will compute the traffic density in the span with the previous RSU. Two fields in the status message code traffic density and weather information (2 bits). This is sent along with the vehicle's coordinates. Vehicles gather this information by means of the mentioned weather on-board sensors, the GPS embedded device and the transmission of periodic one-hop hello messages to compute the traffic density. Also, we assume intelligent vehicles have sensors able to detect that an accident happened.

Step 2: Processing of the data by each RSU and sharing the processed data with the other RSUs in the same road. Each RSU will receive messages regarding traffic statistics from passing vehicles and will update the traffic density statistics by using an exponential weighted moving average (EWMA) to average current and historical values [Mateos Márquez, 2012]. They also update weather information. Then, the RSUs will store the results properly and will share their statistics with the others RSUs in the road through a sub-network they form.

Step 3: Distribution of the processed information RSUs send processed traffic and weather information to passing vehicles, which disseminate that information backwards through the VANET. In case of accident, the message would be sent backwards and also forwards, so that vehicles approaching from ahead will also be warned to avoid further collisions. Vehicles that receive such a message will reduce their speed according to a table in their memory. For instance, in a very congested road segment with rain condition, warning messages inform vehicles to reduce their speed to 40% of the initial driver speed. The driver's assistant device in the vehicles will make the vehicle brake accordingly.

There are two directions in the flow of messages: vehicles-RSU in Step 1, and RSU-vehicles in Step 3. They are of different nature and hence they may receive different treatment. In Step 1, all messages have low priority. It does not matter if some get lost and they do not need to travel as fast as possible. In Step 3, the reachability and the velocity of those warning messages may become crucial (e.g., in case of accident). Hence, we distinguish each priority case with a different approach for the dissemination.

In the case of low priority, it is not mandatory to reach all the destinations in the minimum possible time. There might be many vehicles willing to report traffic information, so a potential bandwidth problem may arise. Thus, we focus on reaching the destinations with the minimum bandwidth usage. This is where our multi-hop broadcast algorithm benefits this application.

More details about the system and the testing results are available in our paper [Garcia-Lozano et al., 2013b].

5.6 Conclusions

In this chapter, we have described our work on a dissemination scheme for roadway scenarios. Our basis is our implementation of the distance-based scheme, that we evaluated in Chapter 4. Our goals were to make it emit as few duplicates as possible in dense traffic and to make sure that messages are carried through the whole ROI even in cases of sparse traffic.

Regarding the redundancy, we have been able to determine that the distance-based mechanism that we have implemented already achieves a ratio of forwarders per receiver near to the theoretical achievable minimum. This means that it is almost impossible to improve the performance in this sense.

With respect to the resilience to disconnections in the vehicular network, we have designed a mechanism that rises the chances of success from 0% to at least 40% in cases of very low traffic density, and from 10% to more than 75% with at least 15 vehicles/km (in total).

As the roadway environment is assumed to be relatively simple, we could take the basic distance-based scheme as it was and optimize it via its configuration parameters. The first step was to work on its ratio of forwarders per receiver. We decided to do this via an analytical study, in which we also had to find the average distance from each relay to the next. We discovered that the scheme is already close to achieving the theoretical minimum. We run simulations in order to validate our findings, with positive results.

We learned in Chapter 4 that its main drawback is the latency, due to the time-based contention at each hop. We have investigated how to minimize it without compromising the coverage and the ratio of forwarders per receiver. Similarly to the previous step, we have done an analytical study of the best configuration given said requisites, and validated it via simulations.

Once we had an optimized scheme for connected vehicular networks, we tackled the problem of eventual disconnections between groups of vehicles. Given that our scheme does not rely on knowledge of the neighbors, we have designed a store-carry-forward mechanism that does not either. The main areas that we had to solve were three: how to detect the necessity to activate the mechanism, when to schedule new retransmissions, and how to select the best relay for maximizing the success of the dissemination. We have evaluated the performance of the complete solution in contrast with that of the basic distance-based scheme from the previous chapter. We have significantly risen the percentage of cases in which a message covers the whole ROI in cases of sparse or very sparse traffic. This has necessarily meant an increase in the number of emitted duplicates.

All in all, each step in our research has led us towards a solution that fulfills to a high degree the requisites that we had set. Via additional simulations, we have checked that even in non-ideal conditions and also when compared to a state-of-the-art solution, our scheme proves to cover the area of interest in a reasonable time and with a minimal number of retransmissions. The results in sparse scenarios are also very positive, though we cannot guarantee that the area of interest will always be covered if the vehicles are very isolated.

In the next chapter we investigate how to create a similar solution for urban scenarios. We will be able to use some of the lessons learned in this chapter, in a setting that presents additional problems as we commented in Section 3.1.

Chapter 6

Optimizations for Urban Environments

Now we work on creating a dissemination solution for cities. According to [Viriyasitavat et al., 2009], the broadcast storm problem is worse in this type of scenario but, at the same time, disconnections are more frequent due to the special characteristics that we mentioned in Section 3.1.

Once more, our starting point is the basic distance-based scheme that we selected in Chapter 4, as it showed the best ratio of forwarders per receiver, and hence, the lowest redundancy. However, given the different nature of this new scenario, its performance may be also different, so the first step will be to try it in this environment. In contrast with the case of roadways, in which we only had to adjust the configuration parameters, we expect that we will have to adapt the scheme in accordance with the singularities of the urban scenario if we want to obtain good results. The store-carry-forward scheme will also have to respond to the new challenges—omni-directionality of the message and difficulty of selecting a suitable relay for carrying, according to [Viriyasitavat et al., 2009] again.

The last step is to assess the performance of our solution via simulations. In addition, we compare it with UV-CAST, the urban counterpart of DV-CAST that we presented in Section 2.2.3.

6.1 Applying the Basic Scheme to Urban Scenarios

In Chapter 4, we learned that a distance-based multi-hop broadcast is best in terms of coverage and duplicate messages savings. Now we are going to test its performance when applied inside a city.

Configuring the Maximum Per-Hop Delay

Let us recall Equation 4.1 of the basic scheme, that determines the distance-based contention wait:

$$t_w = T_{max} \times (1 - d_{min}/r)$$

T_{max} is the maximum per-hop delay, so it directly affects the latency of the scheme. This parameter is important because it helps to prevent situations in which several vehicles try to forward almost simultaneously. In addition, it has to be small enough to consider the scenario almost static during the contention. We determined a proper value for the roadway scenario but, given that urban areas can be very different, we need to find a fitting value for this environment, too.

Given the complexity of the model for urban traffic (see Section 3.1.4), we are going to perform an empirical search via simulations, instead of an analytical study like the one we did for the roadway scenario. We are going to explore a wide range of values for T_{max}, starting in 10 ms and ending in 500 ms (which is the value for the equivalent parameter in UV-CAST used in [Viriyasitavat et al., 2011]). We use the two real city maps shown in Figure 3.3. They consist of a 2 km × 2 km area of Manhattan, New York (Figure 3.3(a)) or around the Castellana Street in Madrid (Figure 3.3(b)). We use a set of traffic densities that go from sparse to dense, in the range from 25 to 100 vehicles per square kilometer. We fix the sender in the center of the area and set a ROI radius of 1 km.

Simulation Results

All the results are shown in figures 6.1 (New York map) and 6.2 (Madrid map). We study the metrics explained in Section 3.2.3: the long-reach success, or portion of cases from all the executed simulation runs in which the dissemination goes further than the second hop; the delivery ratio, as the percentage of vehicles in the scenario that receive the message in cases of long-reach success; the redundancy ratio, or ratio of forwarders per receiver; the total number of lost packets, as an indicator of congestion; the per-hop delay, that accounts for the distance-based and MAC contentions and for the propagation time; and the end-to-end delay, averaged over all the receivers. The points in these graphs and the rest that follow, show the 95% confidence interval.

The long-reach success (figures 6.1(a) and 6.2(a)) and the coverage (figures 6.1(b) and 6.2(b)) remain constant for every traffic density considered in our study. Apart from that, we can see that the redundancy ratio in figures 6.1(c) and 6.2(c) descends when the maximum wait is longer. The reason is that, when the wait is short, there is a high probability that several vehicles will pass the message to the MAC layer almost simultaneously. This leads to the high number of lost packets that we see in figures 6.1(d) and 6.2(d). for values of T_{max} under 350 ms. Regarding the average per-hop delay, (figures 6.1(e) and 6.2(e)) and the end-to-end delay (figures 6.1(f) and 6.2(f)), they are proportional to T_{max}, as expected. Given that this parameter does not affect the success, we search a good trade-off between overhead and latency. The former is improved when the value is greater or equal to 350 ms, while the latency worsens as the value gets higher. So we choose $T_{max} = 350$ ms. This is a rather large value when compared to our chosen value for the roadway scenario, $T_{max} = 18$ ms. The reason is that the broadcast storm problem is very pronounced in urban areas, as pointed out in [Viriyasitavat et al., 2009]. Apart from the higher traffic density, there are multiple paths that connect the source of the message to any vehicle that is in the same connected network. The access to the channel is more difficult, specially if we face collisions due to several relays forwarding at the same time.

6.2 Adaptation to a Bi-dimensional Dissemination

As we commented at the beginning of the current chapter, our logical reasoning is that we can achieve better results than what we have just seen in the previous section, if the basic scheme is modified according to the special characteristics of this type of scenario.

We depict a typical situation in a city in Figure 6.3 to illustrate the case. In this figure, vehicle “src” sends a message that needs to be disseminated. If we apply our basic scheme, the next relay will be vehicle “B”. However, due to the shadowing effect of buildings, vehicle “C” will not receive the message from “src” nor from “B”. Vehicle “A” is the only in line-of-sight with “C”. Thus, vehicle “A” should be the next relay so that “C” can also receive the message.

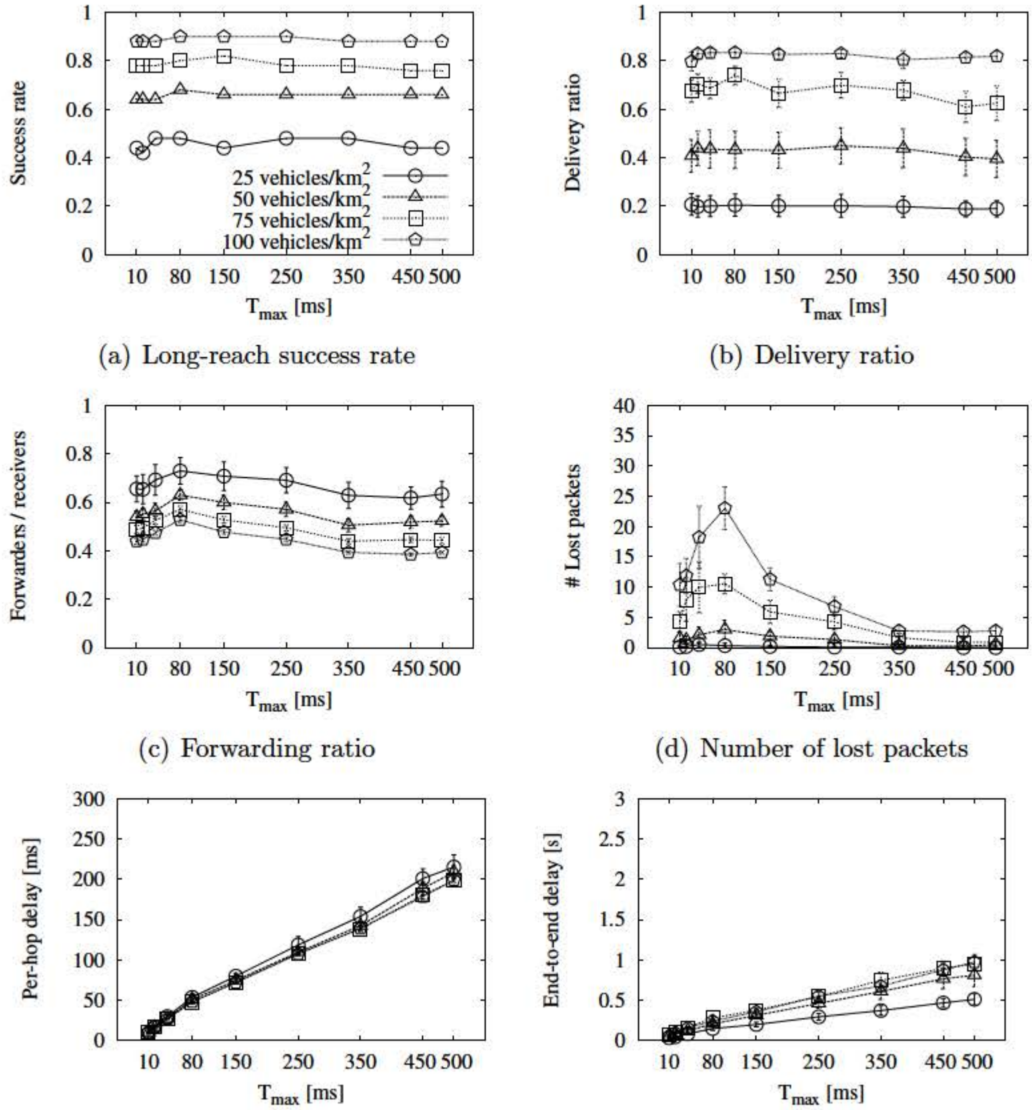
We have broken the problem down into two necessities:

1. omni-directional and circular approach in the dissemination, because targets may be moving in any direction around the source, and

2. an effort to reach neighbors that may be hiding around corners.

We think that both can be tackled by increasing the chances of forwarding at intersections. So, in order to achieve this, a vehicle that receives a new message tries to determine if it is at an intersection. We are going to explore two different approaches for this. The first is using a digital map together with their location coordinates. The other one is interpreting the angle between its direction and the imaginary segment that connects it to the sender. We will describe each one thoroughly below.

Now, as there might be more than one vehicle in the same intersection, we must avoid making them all forward at the same time. We establish a junction-specific time contention, given by a wait called t_j. The equation that determines its value is related to each of the detection techniques that we are going to use. While vehicles located in intersections use this timer, the others apply the distance-based scheme, waiting t_w (see Equation 4.1). That is, the junction contention only affects the vehicles in the same intersection. And conversely, a vehicle located at an intersection will ignore every duplicate except if it comes from the same one. We have depicted this execution flow in Figure 6.4.



(a) Long-reach success rate

(b) Delivery ratio

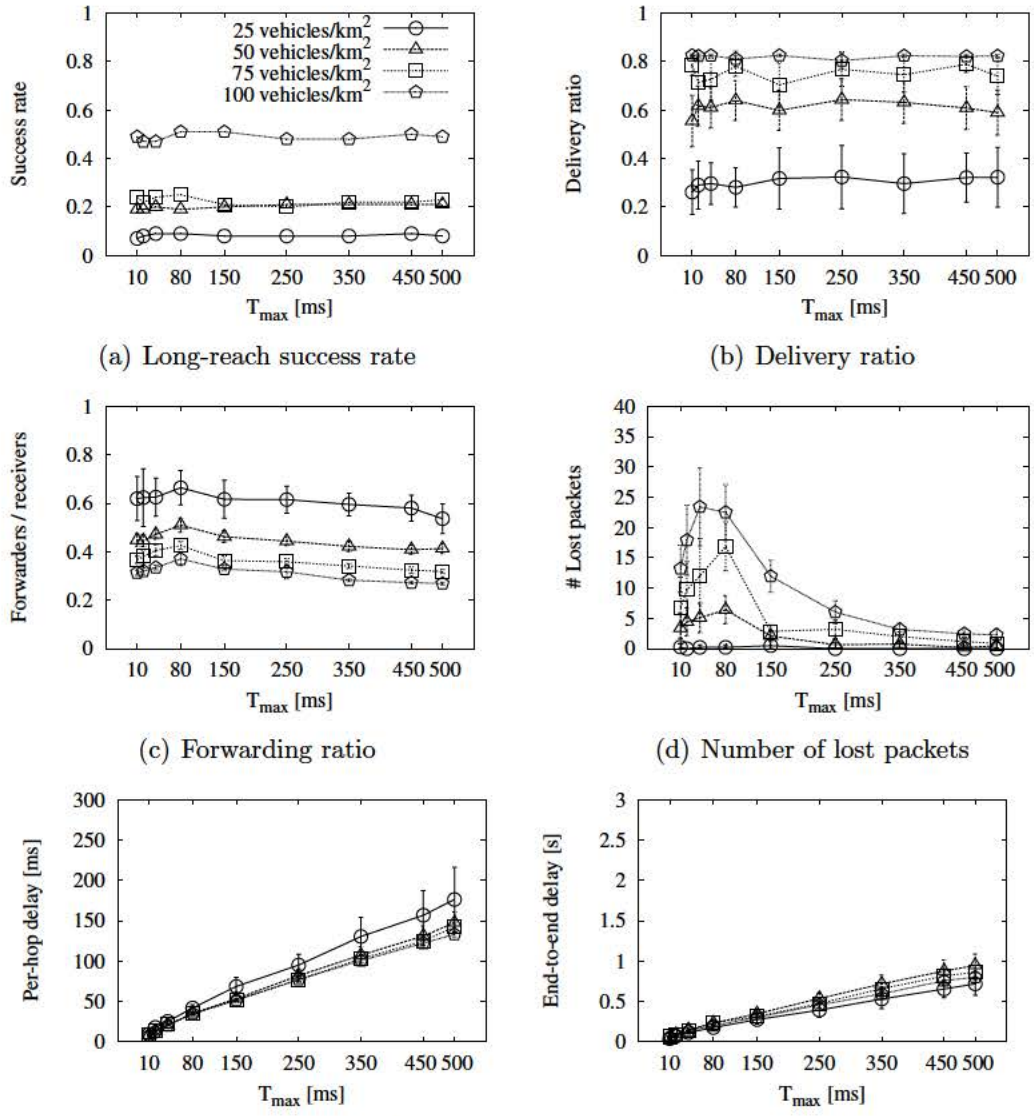
(c) Forwarding ratio

(d) Number of lost packets

(e) Average per-hop delay

(f) Average end-to-end delay

Figure 6.1: Simulation results of the basic scheme with different T_{max} values in the New York scenario.



(a) Long-reach success rate

(b) Delivery ratio

(c) Forwarding ratio

(d) Number of lost packets

(e) Average per-hop delay

(f) Average end-to-end delay

Figure 6.2: Simulation results of the basic scheme with different T_{max} values in the Madrid scenario.

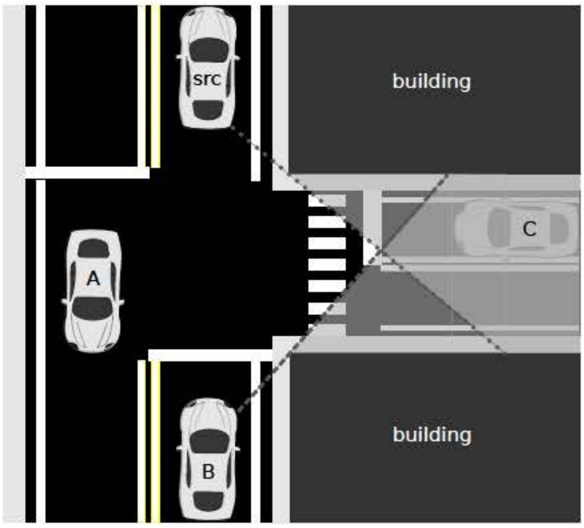


Figure 6.3: Shadowing problem in urban environments

In the following sections, we detail and evaluate the two techniques for intersection identification: the use of digital maps and the calculation of the message reception angle.

6.2.1 Map-Based Adaptation

The first method for detecting junctions that we are considering is the use of a digital map. At the moment of receiving a new packet, a vehicle checks its coordinates to determine if it is at an intersection or not. Given the case, it will use the map again to find out the distance to the junction center, d_{center}. It will use this distance to compute a different contention delay, as shown in Equation 6.1:

$$t_j = T_j \times (d_{center}/r_{junction}) \tag{6.1}$$

Here, T_j is the maximum wait time for vehicles in junctions and $r_{junction}$ is the radius of the given intersection. This radius can be obtained from the digital map, too. In this case we want to prioritize the vehicle that is closest to the intersection center, in order to reach as many other vehicles as possible.

We determined in Section 6.2 that a vehicle located at an intersection will ignore every duplicate except if it comes from the same intersection. If it is using the map-based method, it will be easy to check the other's location and its own one in the map and see if they belong to the same intersection.

Tuning of T_j

Similarly to T_{max} in our basic scheme, we need to find a suitable value for T_j. This parameter is the maximum wait for vehicles in junctions. We want vehicles in intersections to wait, at most, the same as vehicles applying the general distance-based contention equation. Thus, it must be less or equal to T_{max}.

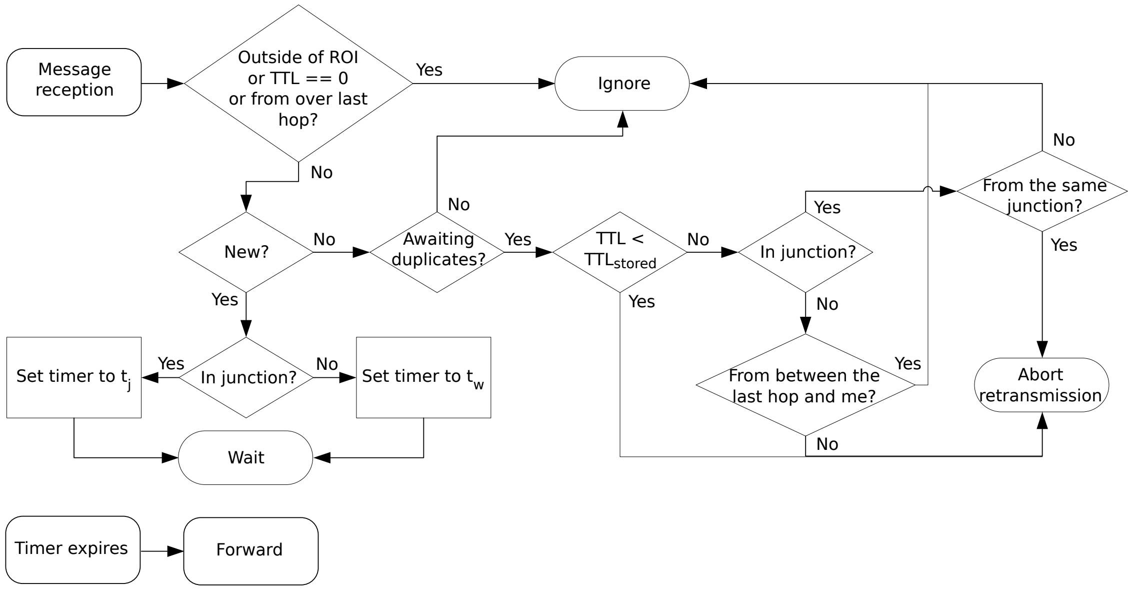
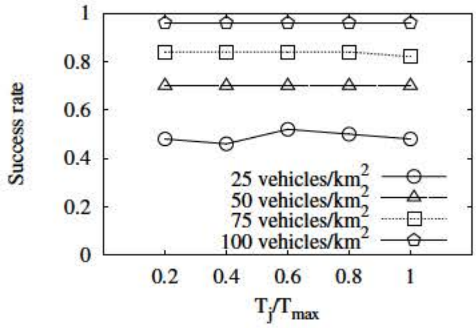


Figure 6.4: Flow diagram of the urban dissemination scheme.

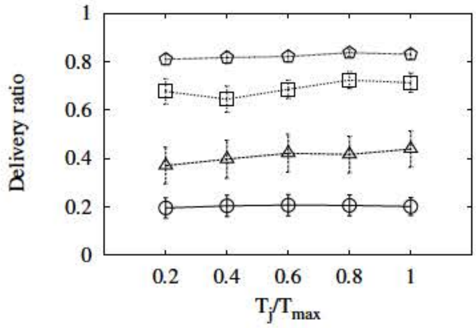
We use the value we found above, $T_{max} = 350\,\text{ms}$, in the map-based variant to study the effect of T_j alone. In order to better understand the simulated points, the x-axis of the graphs in figures 6.5 and 6.6 represents the relation between T_j and T_{max} instead of absolute values. There, we can see that the success, be it in terms of long reach (figures 6.5(a) and 6.6(a)) or delivery ratio (figures 6.5(b) and 6.6(b)), is not related to this waiting time either. We also find a very limited effect in the redundancy ratio from figures 6.5(c) and 6.6(c). The slight rise is caused by vehicles in a junction that are also the furthest from the previous relay. They wait so much that another vehicle forwards first, though it does not inhibit them. It is almost balanced out by the slightly higher number of vehicles that forward from junctions (figures 6.5(d) and 6.6(d)) when their wait is shorter. Again, a very short maximum delay has the same problems of redundancy and losses as T_{max} did, and that we can see in figures 6.5(e) and 6.6(e). The average per-hop delay, shown in figures 6.5(f) and 6.6(f), is clearly influenced by the vehicles that have to wait less because they are in intersections. However, this effect is hidden in the average end-to-end delay, as we can appreciate in figures 6.5(g) and 6.6(g). Following a similar reasoning to that for T_{max}, we find that $T_j/T_{max} = 0.6$ is the best compromise between losses and delay. This corresponds to $T_j = 210\,\text{ms}$.

6.2.2 Angle-Based Adaptation

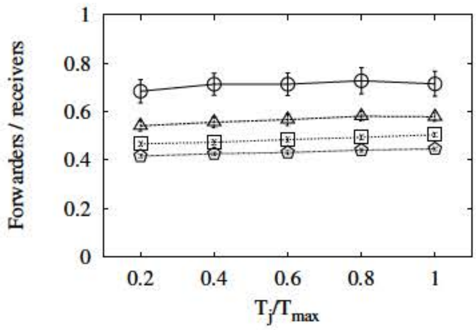
As a different alternative, we propose that vehicles pay attention to the angle of the previous sender with respect to their own trajectory. We assume that if it is more or less close to a right angle to either side, the message comes from another street. A problem of urban scenarios is that the signal may bounce of and be redirected by buildings, parked cars, street signs, etc. Therefore, learning the reception angle from



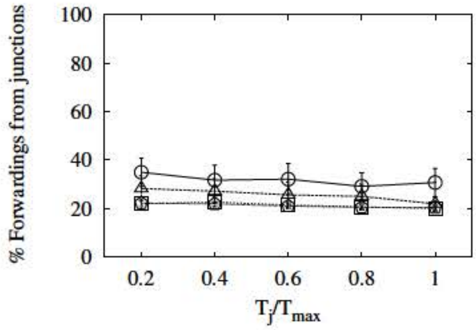
(a) Long-reach success rate



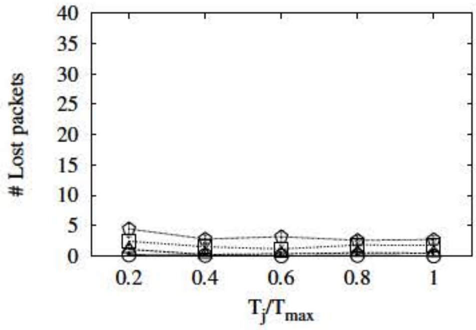
(b) Delivery ratio



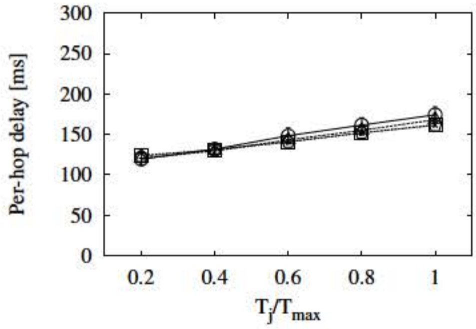
(c) Forwarding ratio



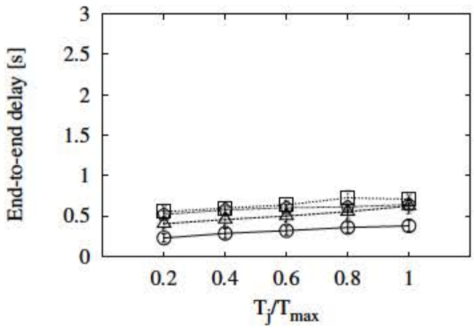
(d) Portion of relays from junctions



(e) Number of lost packets

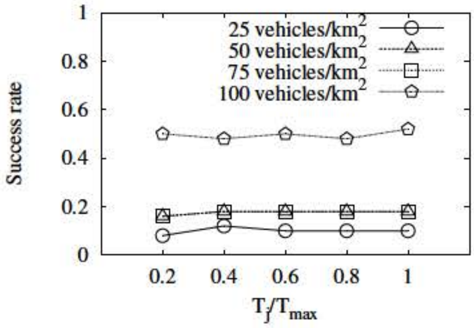


(f) Average per-hop delay

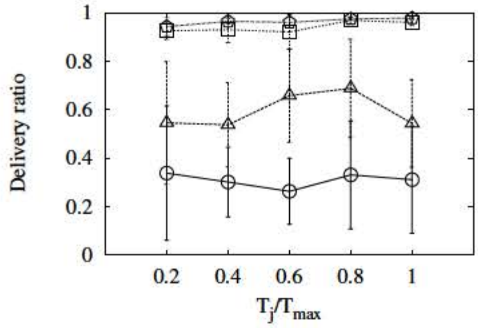


(g) Average end-to-end delay

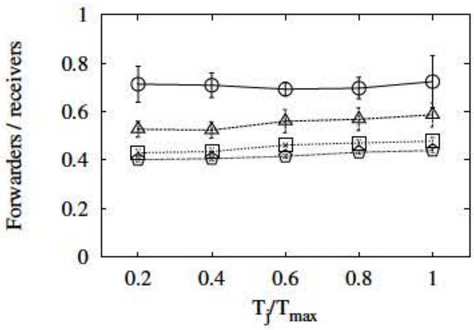
Figure 6.5: Results of the map-based scheme with fixed T_{max} and different T_j values in the New York scenario.



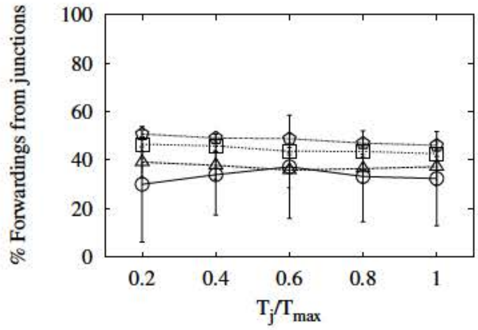
(a) Long-reach success rate



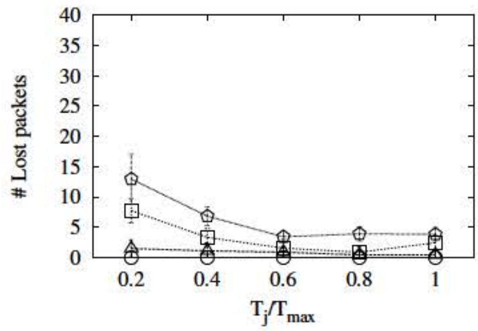
(b) Delivery ratio



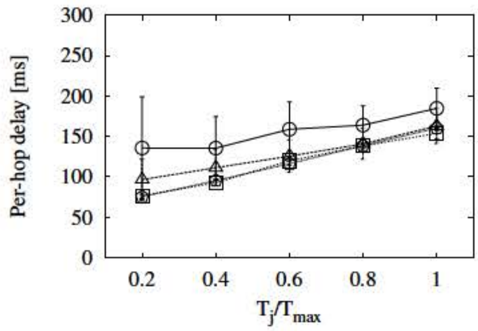
(c) Forwarding ratio



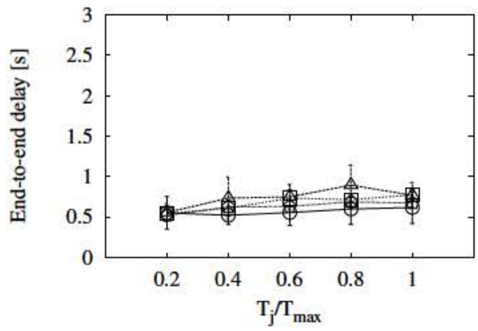
(d) Portion of relays from junctions



(e) Number of lost packets



(f) Average per-hop delay



(g) Average end-to-end delay

Figure 6.6: Results of the map-based scheme with fixed T_{max} and different T_j values in the Madrid scenario.

City	Minimum	Median	Maximum
New York	2.34 m	9.89 m	49.69 m
Madrid	2.56 m	9.24 m	45.09 m
Rome	2.29 m	9.64 m	81.62 m
Cologne	2.31 m	9.61 m	77.80 m

Table 6.1: Statistics of the widest diagonal in junctions in several cities.

the antenna may be misleading. To avoid this, we calculate it based on the other's reported location and the receiver knowledge of its own trajectory. We will use two threshold angles, α_{min} and α_{max}, in order to set a range for the condition evaluation. If the reception angle falls between the two of them, the vehicle is considered to be at an intersection. It cannot determine the distance to the intersection center, unlike in the map-based adaptation, so next it waits a random amount of time, t'_j, from the distribution in Equation 6.2.

$$t'_j \sim U(0, T_j) \tag{6.2}$$

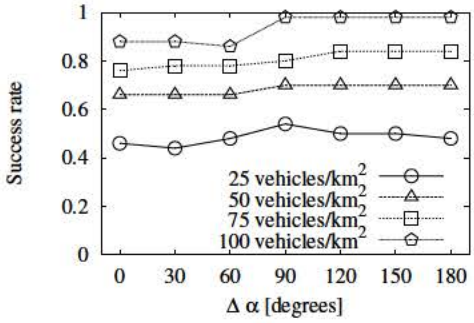
Again, the first vehicle to forward inhibits the rest in the intersection to do the same. When using the angle-based method, it will need to use a generic threshold distance, d_j. If the other vehicle is closer than this distance, we assume that it is located in the same intersection.

It did not make sense to try to adjust d_j by simulations because it is highly dependent on the given city and we would only overfit it to our scenario. Instead, we have studied the widest diagonal in junctions from a set of four different city maps: New York (USA), Madrid (Spain), Rome (Italy) and Cologne (Germany), available via OpenStreetMap. The results are shown in Table 6.1. The median—the most usual value—was, respectively, 9.89 m, 9.24 m, 9.64 m and 9.61 m. Accordingly, we have set $d_j = 10$ m.

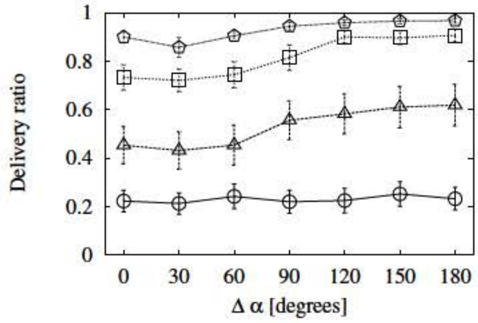
Tuning of $\Delta\alpha$

We have already assigned proper values to T_{max} and T_j. If we want to apply this method, we also need to find out the angle thresholds, α_{min} and α_{max}, They will let us determine if a vehicle is receiving a message from a different street, by comparing the reception angle with these two thresholds. The reception angle is calculated by using the relay's reported location and the receiver knowledge of its own trajectory. We define $\Delta\alpha$ as the difference between α_{max} and α_{min}.

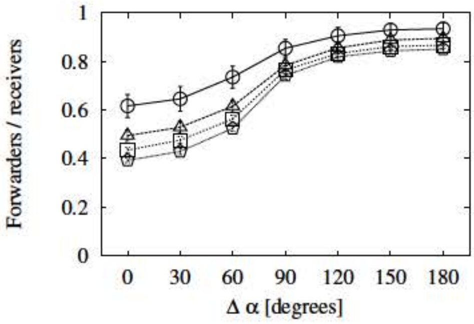
We can observe the effect of this parameter in figures 6.7 (New York scenario) and 6.8 (Madrid). When $\Delta\alpha$ is a flat angle to either side, every reception angle indicates that the vehicle is at an intersection. Hence, all the retransmissions are assumed to be done from intersections, because every vehicle believes it is in one. And when $\Delta\alpha$ is $0\,^\circ$, no one considers itself inside a junction, so none of the retransmissions is done from one. $\Delta\alpha$ does not affect the success of the scheme, as we can see in the graphs that represent the long-reach success (figures 6.7(a) and 6.8(a)) and the delivery



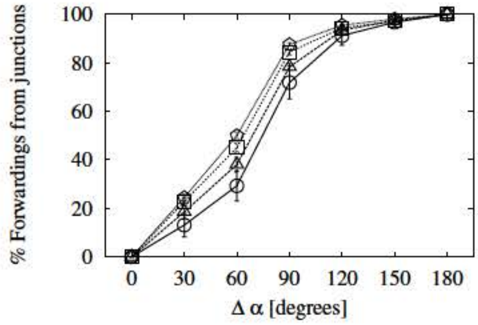
(a) Long-reach success rate



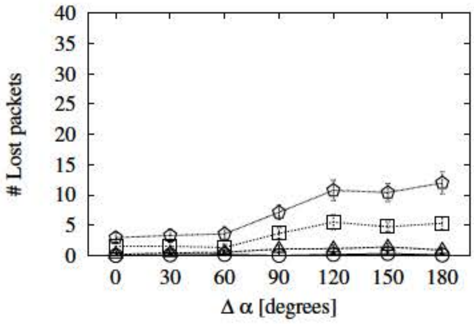
(b) Delivery ratio



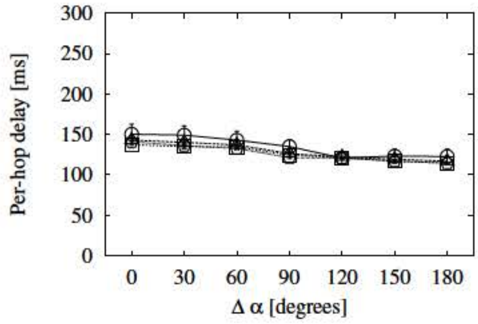
(c) Forwarding ratio



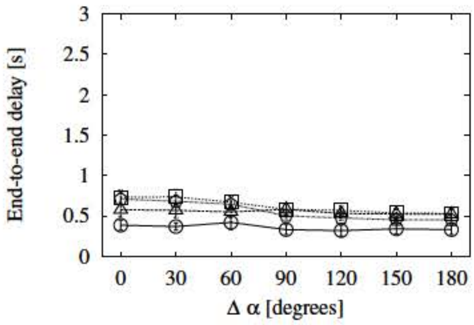
(d) Portion of relays from junctions



(e) Number of lost packets

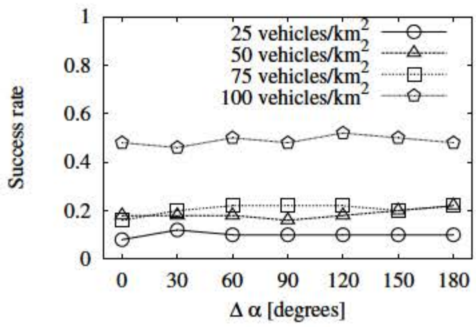


(f) Average per-hop delay

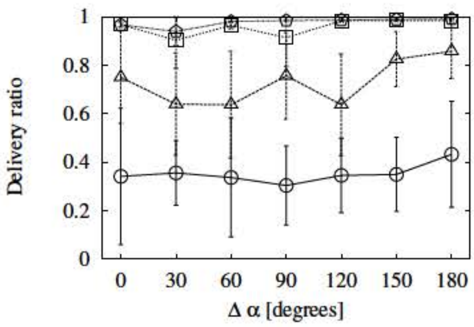


(g) Average end-to-end delay

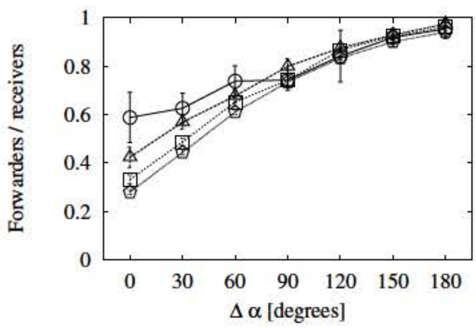
Figure 6.7: Results of the angle-based scheme with fixed T_{max} and T_j, and varying $\Delta\alpha$ in the New York scenario.



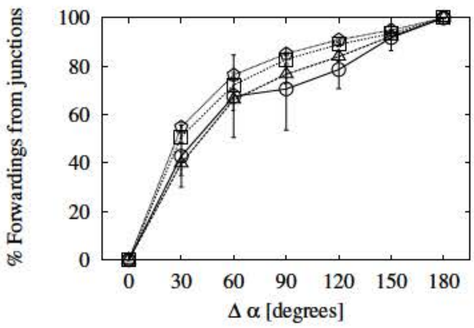
(a) Long-reach success rate



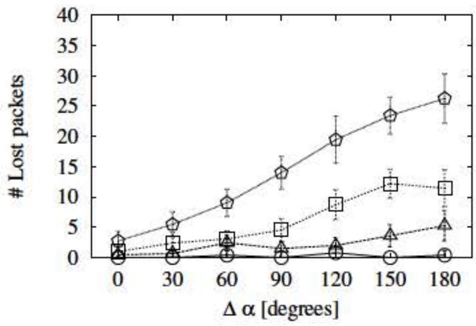
(b) Delivery ratio



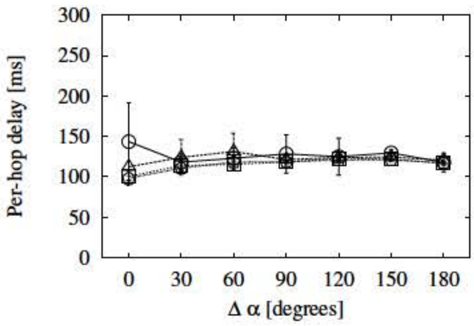
(c) Forwarding ratio



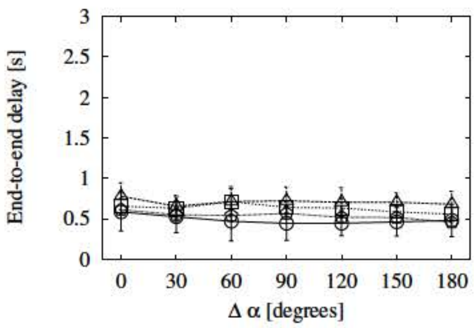
(d) Portion of relays from junctions



(e) Number of lost packets



(f) Average per-hop delay



(g) Average end-to-end delay

Figure 6.8: Results of the angle-based scheme with fixed T_{max} and T_j, and varying $\Delta\alpha$ in the Madrid scenario.

ratio (figures 6.7(b) and 6.8(b)). However, it does have a strong impact on the forwarding ratio, as shown in figures 6.7(c) and 6.8(c). When the parameter's value is a wide angle, many vehicles consider themselves inside a junction. We can see this in figures 6.7(d) and 6.8(d). Because of this, the number of retransmissions grows significantly. This leads to many lost packets, as seen in figures 6.7(e) and 6.8(e), specially for values bigger than 60 °. Regarding the latency, we see quite flat curves for the average per-hop (figures 6.7(f) and 6.8(f)) and end-to-end (figures 6.7(g) and 6.8(g)) delays. The reduction in latency that we could expect when most vehicles have a shorter wait time is compensated with the long MAC contentions. All in all, given the high packet loss and latency with wide angles, we limit this parameter to $\Delta\alpha = 60\,^{\circ}$.

6.3 Comparative Evaluation of the Schemes

In this section, we compare the basic scheme (as in Section 6.1) and the two variants with their chosen configuration. For reference, we have included the simulation results of a simple flooding scheme with a random jitter before forwarding.

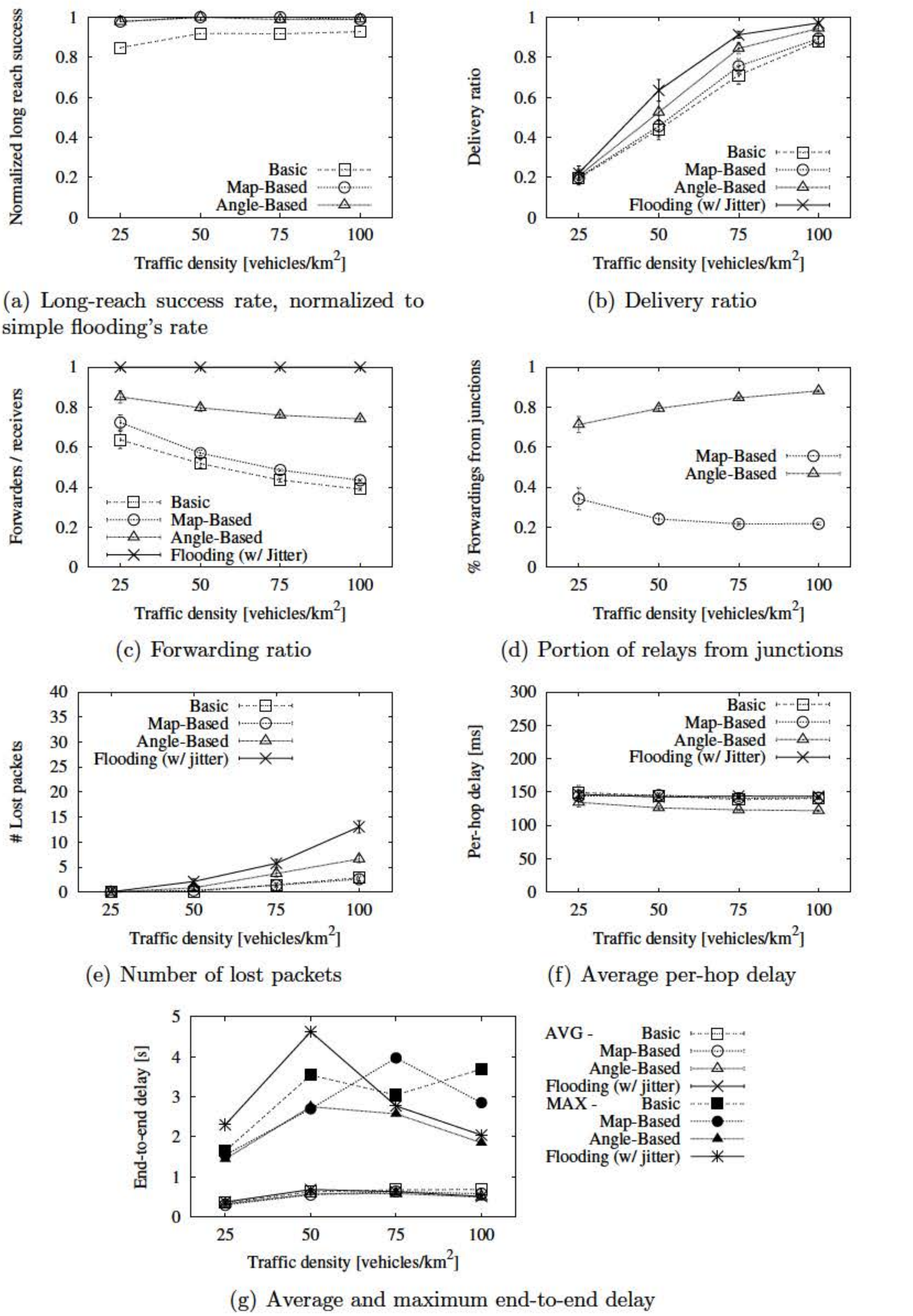
The flooding scheme is configured so that when a vehicle receives a new message, it selects a random delay from an uniform distribution. We have selected the maximum value of the delay distribution so that the mean would approximately match the average per-hop delay of the other schemes in the comparison. This way, the dissemination through the whole ROI takes a similar time for all of them. This is important because, as time passes by, vehicles will be entering the ROI (becoming new targets) or leaving it (becoming unreachable). By keeping the end-to-end delays comparable, the number of reachable targets is consistent, too.

Like the previous simulations in this chapter, we use two real maps from a 2 km × 2 km city section of New York (Figure 3.3(a)) and Madrid (Figure 3.3(b)). Again, the traffic densities go in the range from 25 to 100 vehicles per square kilometer. The origin of the message is a fixed unit in the center of the scenario and the preset radius of the ROI is 1 km.

The simulation results can be seen in Figure 6.9 for the New York scenario, and in Figure 6.10 for the Madrid one. The first thing we want to point out is the similarities and differences between the results from both scenarios, in these graphs and all the preceding ones. We can appreciate a clear difference in absolute values, that confirms what other works (like [Fogue et al., 2012] and [Viriyasitavat et al., 2011]) had already found out—different scenarios yield different results. But we can also see that the tendency of the curves and the inflection points are the same. Therefore, we can extrapolate conclusions from one scenario that will be valid for the rest.

Regarding the schemes, we can see the long-reach success of each one, normalized to that achieved by simple flooding, in figures 6.9(a) and 6.10(a). The three studied schemes are close to the flooding, being the two urban adaptations the ones with highest ratios. We see similar results for the delivery ratio (figures 6.9(b) and 6.10(b)).

In return for the higher coverage, the urban schemes require more duplicates.



(a) Long-reach success rate, normalized to simple flooding's rate

(b) Delivery ratio

(c) Forwarding ratio

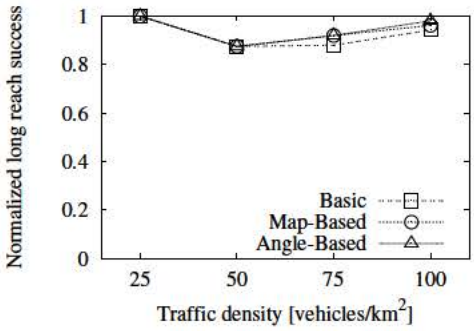
(d) Portion of relays from junctions

(e) Number of lost packets

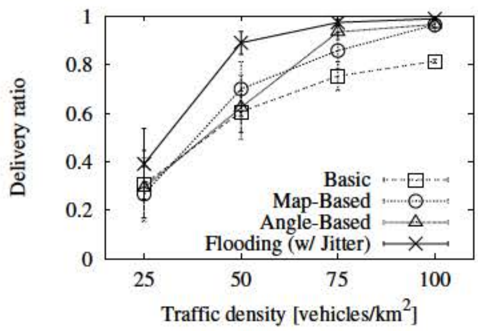
(f) Average per-hop delay

(g) Average and maximum end-to-end delay

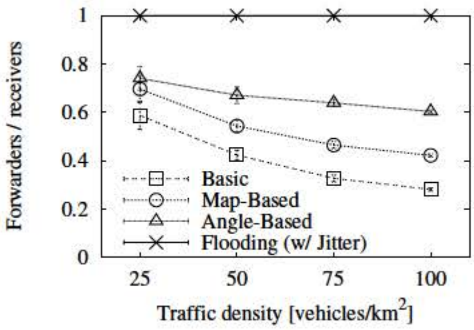
Figure 6.9: Comparative of the different schemes with the final values in the New York scenario.



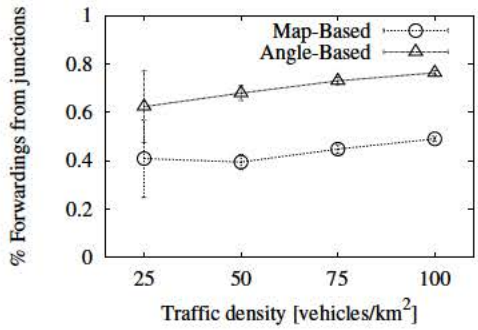
(a) Long-reach success rate, normalized to simple flooding's rate



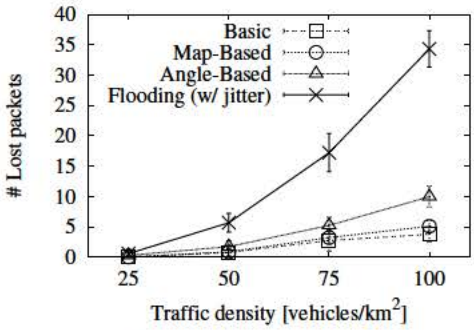
(b) Delivery ratio



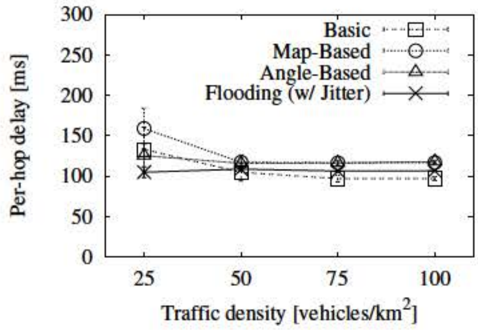
(c) Forwarding ratio



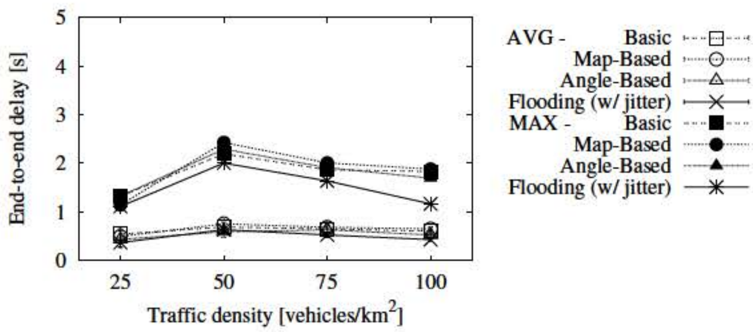
(d) Portion of relays from junctions



(e) Number of lost packets



(f) Average per-hop delay



(g) Average and maximum end-to-end delay

Figure 6.10: Comparative of the different schemes with the final values in the Madrid scenario.

This can be noticed in the forwarding ratio in figures 6.9(c) and 6.10(c), as well as in the number of lost packets in figures 6.9(e) and 6.10(e). We can see that the angle-based scheme is the worst in this sense, with high ratios of forwarders per receiver even in high densities. We can see in Figure 6.9(d) and Figure 6.10(d) that this is due to the greater number of vehicles forwarding from junctions. An important factor for this is the definition of intersection in each urban scheme. In the angle-based scheme, a vehicle may be physically close to a junction rather than in it, but it will consider itself inside it, whilst the map-based scheme will not allow this. In addition, a map does not account for sidewalks and other open spaces that let the signal travel. Another factor is the distance threshold used in the angle-based scheme to decide if a neighboring relay is in the same intersection as a waiting vehicle. In wide junctions like a big roundabout, it may be too short, letting two or more vehicles in the same intersection forward the message.

Lastly, figures 6.9(f)–6.9(g) and 6.10(f)–6.10(g) show the latency of the schemes. Together with the average value, we show the maximum end-to-end delay. Due to the shorter wait for vehicles in intersections, the two urban schemes have a slightly shorter average per-hop delay, though this effect is softened in the average end-to-end delay.

In general, our conclusion is that the adaptations for urban environments improve the success in the dissemination with regard to the basic scheme, though the latter also offers reasonably good results and with a lower redundancy. Between the two adapted schemes, the angle-based variation achieves a slightly higher coverage than the map-based one at the cost of a relevant overhead. Hence, we think that the map-based option offers a good compromise between gains and losses, and that any of the basic or the map-based schemes would be a good choice for the urban environment.

6.4 Resilience to Short Disconnections

A fact that we must take into account is that we will face frequent disconnections in the vehicular network. The many obstacles that are present in cities artificially break the network and low traffic densities lead to the same outcome. With the current scheme, the message dissemination stops there.

Depending on the application of the information, this can pose a problem or not. The source may opt to emit the message periodically and so, vehicles entering the area of interest later on can receive it, too. In other cases, though, it may be interesting to overcome eventual disconnections. We discuss about how to integrate a store-carry-forward mechanism in our solution for cities in this section.

6.4.1 Design of the Mechanism

Being a totally different scenario, we cannot apply our store-carry-forward approach for roadways to an urban scenario. First of all, vehicles' relative locations are not only behind or in front of another anymore. The message travels omni-directionally and so do the vehicles. Hence, many of the measures we considered in Chapter 5 cannot be applied here. However, there are two design principles from the roadway approach that we intend to include in this design, that we proceed to explain.

Acknowledging and Taking Over as Relay

When a vehicle forwards a message, it may reach new recipients or none at all. If there is any, it will start a new contention and there will eventually be a retransmission. Otherwise, no one will forward the message again. So, if disconnections cannot be ignored and we need to apply a healing mechanism, silence after a retransmission will be the sign that it did not reach any new node. A relay that does not hear a subsequent retransmission, will have to forward again in the future in the hopes to find new neighbors. This retransmission will happen at some point in the following interval:

$$(W, W + max(t_w, t_j)] = (W, W + max(T_{max}, T_j)] = (W, W + T_{max}] \tag{6.3}$$

After the assessment time for receiving almost simultaneous duplicates, W, nearby vehicles will start one of the two types of contention, depending on the applied algorithm and their position: a regular distance-based contention (given by t_w) or a junction contention (given by t_j). Both of them have a maximum length of T_{max} and T_j, respectively. In Section 6.2.1 we explained that T_j must be less or equal to T_{max}. Hence, the maximum time a relay will wait for a new one is $W + T_{max}$.

Conversely, a new duplicate with lower TTL in said interval acts as an implicit acknowledge of reception and taking over as relay. We talked about adopting this same approach for store-carry-forwarding in roadways in Section 5.3.

Waiting Before Forwarding Again

When we discussed the case of roadways in Section 5.3, we adopted **two measures** about how much to wait before forwarding for a second time or more:

1. As we do not use beacons in our scheme, we would not rely on receiving them from vehicles that do not appear in each vehicle's neighbor database.

2. The best time to forward again is after the vehicle has moved out of the area that it covered with its first retransmission. In order to suit the speed of not only the relay, that may be slow, but also the nearby vehicles, we opted to use the maximum allowed speed, v_{limit}. Then, the right time to forward again was every r/v_{limit} (Equation 5.13), being r our reception range.

Measure 1 is still applicable to the urban scenario, as our adapted scheme does not relay on a neighbor database. In regard with measure 2, we are going to try different approaches to finding the best delay between repeated retransmissions from the same vehicle. We have come up with three different alternatives:

Speed-Adaptive A possibility is to modify Equation 5.13 in order to adapt the interval to the vehicle's speed:

$$r/v_{relay} \tag{6.4}$$

r is the vehicle's reception range and v_{relay}, its current speed. The reasoning is that vehicles in cities halt frequently, due to traffic lights, yieldings, pedestrian crossings or jams. It would not make sense to forward at a fixed interval if the vehicles in that spot are not moving or doing it very slowly. If v_{relay} is 0 km/h, it must be checked again after a few seconds in order to compute a finite delay.

Fixed Interval This would be the most similar option to what we included in the mechanism for roadways because the period is fixed. The delay given by Equation 5.13 might be too long, as the speed limit in urban areas is significantly lower than in roadways. We are going to test a wide range of values, from short intervals (every 0.5 s) up to the long ones that would result in applying the speed-adaptive method at 5 km/h. This range includes the period used in roadways, and the corresponding value to the speed limit in urban areas.

Map Polling Finally, we can make the retransmissions happen when the relay is passing through an intersection. This could help the message spread in other directions than the forwarding vehicle's. Our way to implement this will be via a "map polling"—the vehicle checks its coordinates in the digital map at a fixed interval. If at the time it is in an intersection, it forwards. Otherwise, it waits for the next check. This will let us test if we can avoid forwarding at every junction (that will surely happen with a low frequency) or not (by using a short period).

The reasoning for the speed-adaptive approach brings on the case for a **third measure**: not forwarding if the vehicle has not moved since the last retransmission. If the vehicle has remained stopped, probably the vehicles around it are still the same and the retransmission would be useless.

All in all, the complete store-carry-forward functionality is supported by the use of a packet timer. Such a timer can substitute the contention timer in any of the schemes that we consider for use in cities, as in Figure 6.11.

6.4.2 Performance Evaluation

In this section, we explore the results of applying this store-carry-forward design with either of the three waits. We test the different options with basic scheme. This time, the only scenario for the simulations is the 2 km × 2 km area from Manhattan, New York, shown in Figure 3.3(a). As we have explained above, one scenario will be enough to draw comparative conclusions.

Given that store-carry-forward achieves a higher coverage over time by increasing the number the duplicates, we show the evolution of the performance along the first 450 s since the source emits the message. We have chosen four instants to measure each metric: after 1 s, 5 s, 250 s and 450 s. The first milestone corresponds to the first moments of the dissemination, before store-carry-forward can be applied. The

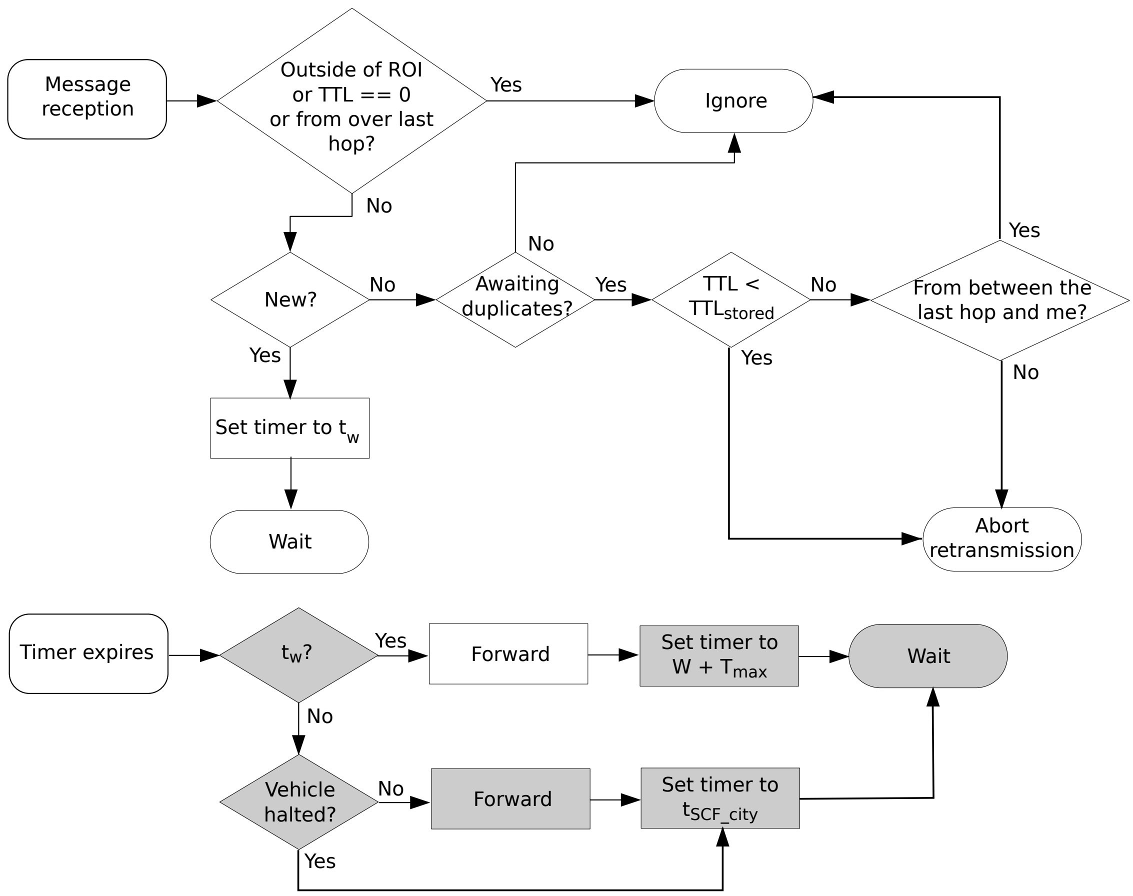


Figure 6.11: Flow diagram of the basic dissemination scheme with the urban store-carry-forward mechanism. The elements added or modified by the latter are shadowed.

next three show the evolution until all the vehicles that were in the scenario at the beginning of the dissemination have left it.

In this lapse, vehicles keep entering and leaving the scenario (though the density is kept constant by the VACaMobil extension, as explained in Section 3.2.2). At each milestone, we need to take into account the activity of the vehicles that have been in the scenario up until that point. The graphs that show the performance results in the following sections reflect this facet.

Speed-Adaptive Approach

Figures 6.12 to 6.14 contain the simulation results when using Equation 6.4 to compute the interval between subsequent retransmissions. In this case we have included the results of applying the store-carry-forward mechanism to the map-based urban scheme, too. It is worth noticing that the results of the basic distance-based and map-based adapted schemes are practically the same in the long run. We have cut down on the number of graphs for brevity, but this aspect is also true for the fixed interval and the map polling strategies.

In Figure 6.12, we can see the delivery ratio along with the portion of vehicles that acted as relays, as well as how many of them applied store-carry-forward. Figures 6.12(a) and 6.12(b) correspond to a low traffic density and thus they show a higher proportion of relays than what we see in figures 6.12(c) and 6.12(d). We observe that the portion of relays applying store-carry-forward is 0% until after 5 s since the beginning of the dissemination. The reason is that the speed-adaptive period is larger than that. Given our configured reception range, vehicles should be traveling at more than 167 km/h in order to compute a shorter delay. The absolute portion of relays that apply store-carry-forward after 450 s is slightly higher in the scenarios with 100 vehicles/km^2. This is, in fact, relatively much lower than in the sparse traffic situations. We could expect this effect, given that large gaps are more prone to occur in the latter.

In Figure 6.13, we can see the average number of duplicates that were necessary for the dissemination of a single message, together with how many of them were the second or more retransmission from the same relay. As we could already appreciate in the previous set of graphs, the proportion of messages due to store-carry-forward is reduced. The number of messages shows a predictable rise in time as new vehicles enter the ROI and become targets and relays.

Finally, we see the general efficiency in a glance in Figure 6.14. The ratio of duplicates by receivers goes up slowly and the number of retransmissions does not reach the accumulated number of targets after 450 s. We will be able to put this information in context when we compare this approach with the other two.

Fixed Interval Approach

In figures 6.15–6.17, we show the simulation results of applying store-carry-forward to the basic dissemination scheme with this approach. From all the tested values, we have selected for representation the three smaller (every 0.5, 5 and 10 s).

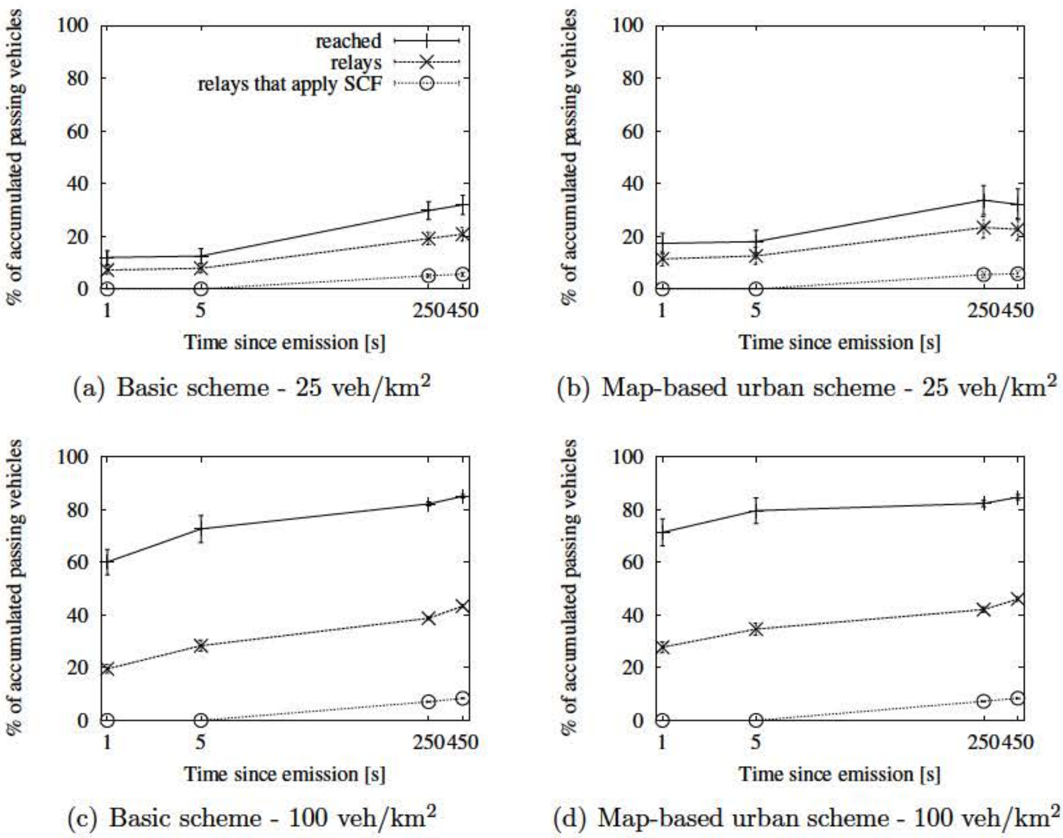


Figure 6.12: Involved vehicles with the speed-adaptive approach for store-carry-forward in the New York scenario.

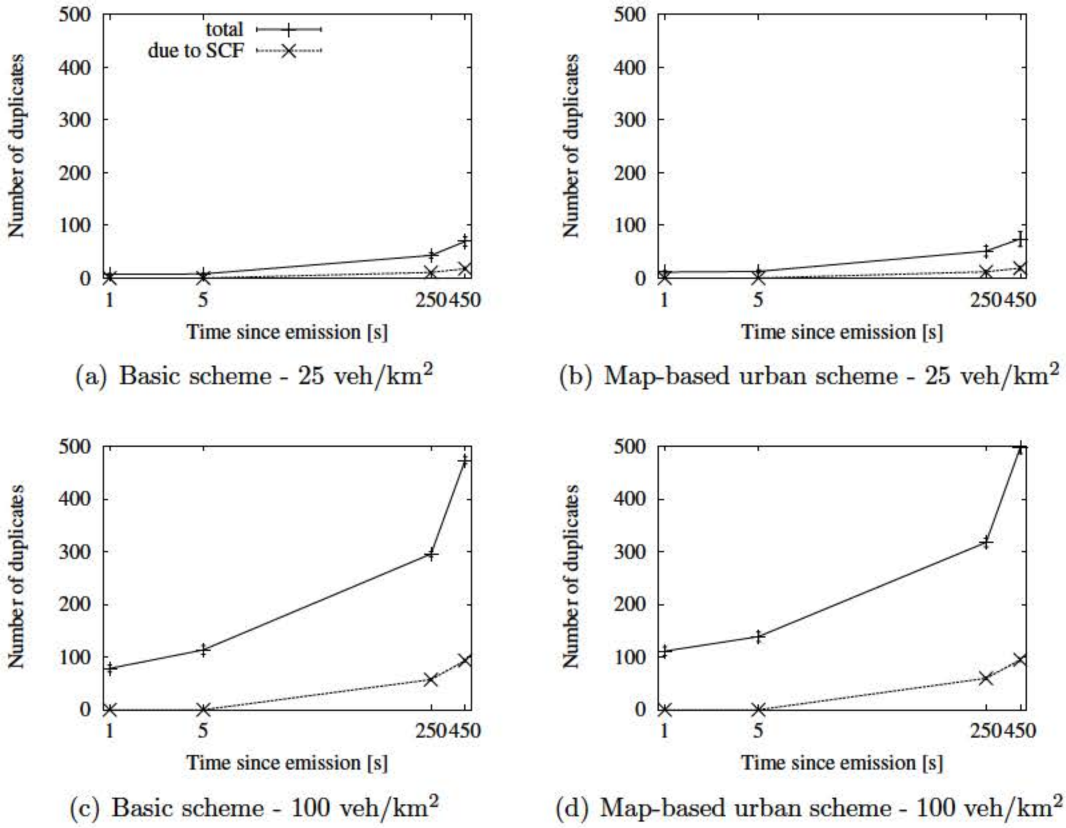


Figure 6.13: Sent duplicates with the speed-adaptive approach for store-carry-forward in the New York scenario.

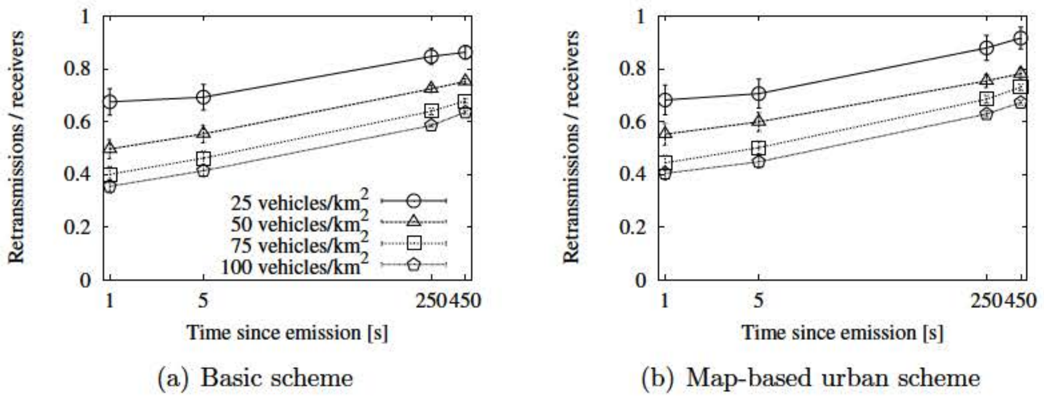
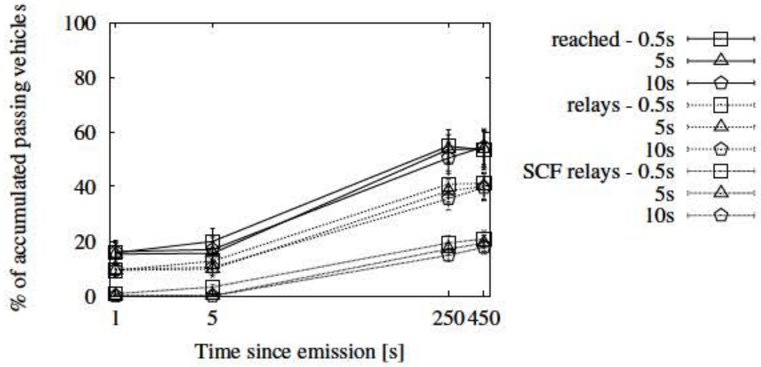
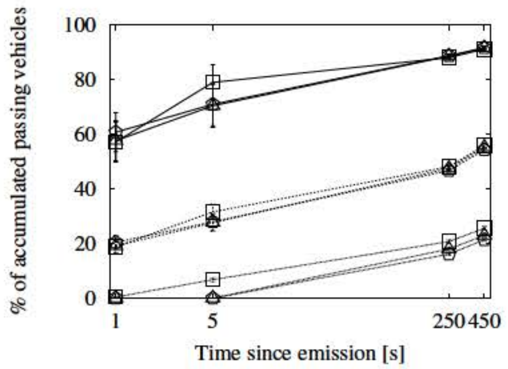


Figure 6.14: Forwarding ratio, or the relation between sent duplicates and receivers with the speed-adaptive approach for store-carry-forward in the New York scenario.



(a) Basic scheme - 25 veh/km^2



(b) Basic scheme - 100 veh/km^2

Figure 6.15: Involved vehicles with the fixed interval approach for store-carry-forward in the New York scenario.

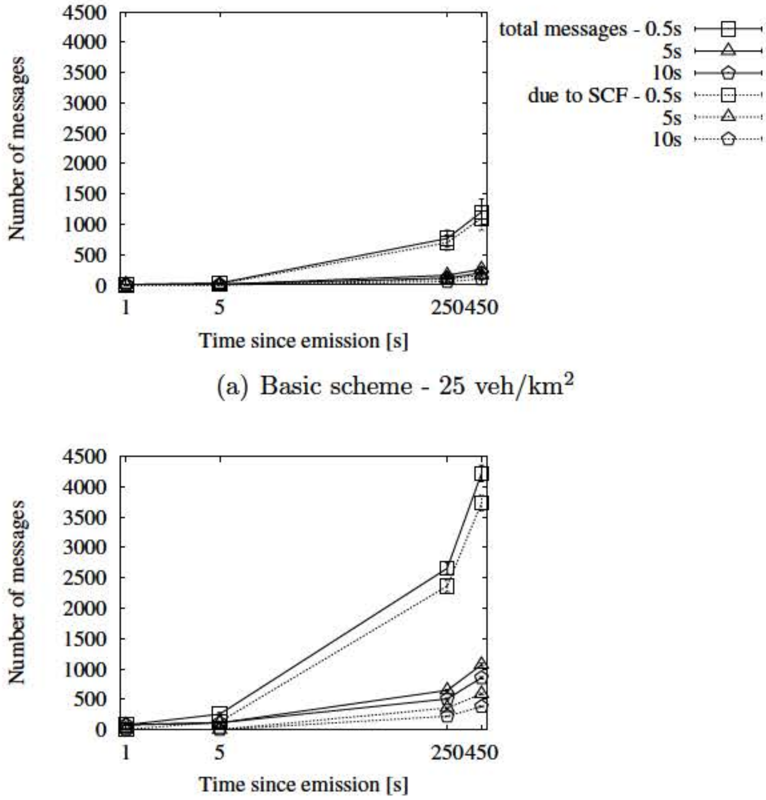
First, we can see that the aspects we have discussed about the speed-adaptive interval are present in these results, too. So we proceed to evaluate how the configured interval length affects the performance.

If we look at Figure 6.15, we can see that changing the actual configured value does not have a significant impact on the delivery ratio. However, the number of duplicates observed in Figure 6.16 is clearly higher when the retransmissions due to store-carry-forward are more frequent. All this leads to the higher ratios of retransmissions per reached vehicle that we can see in figures 6.15(a) and 6.15(b) when compared to the other two.

Map Polling Approach

We can see the simulation results for this strategy in figures 6.18 to 6.20.

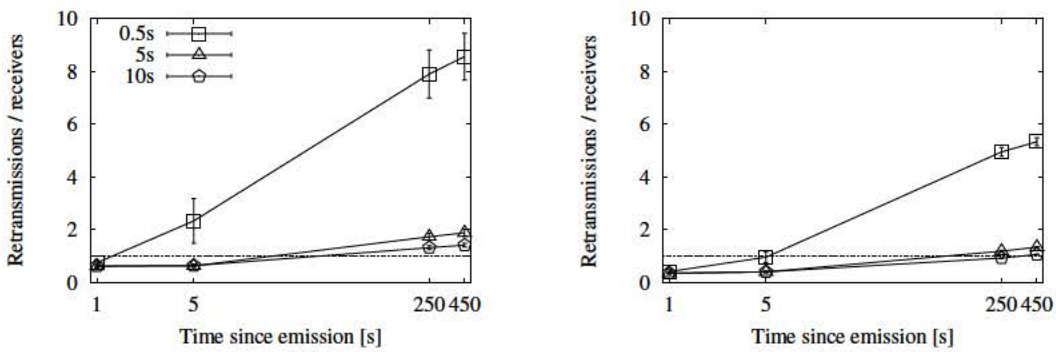
The number of reached vehicles, as seen in Figure 6.18, is slightly lower when the polling period is longer. This is due to the consequent reduction in retransmissions, that we can verify in Figure 6.19. Additionally, we can see that the highest polling frequency causes a higher proportion of duplicates cause by store-carry-forwarding—up to a half of the duplicates. This contrasts with the results of the other two considered values, that are in the line of the two previous options. It is



(a) Basic scheme - 25 veh/km^2

(b) Basic scheme - 100 veh/km^2

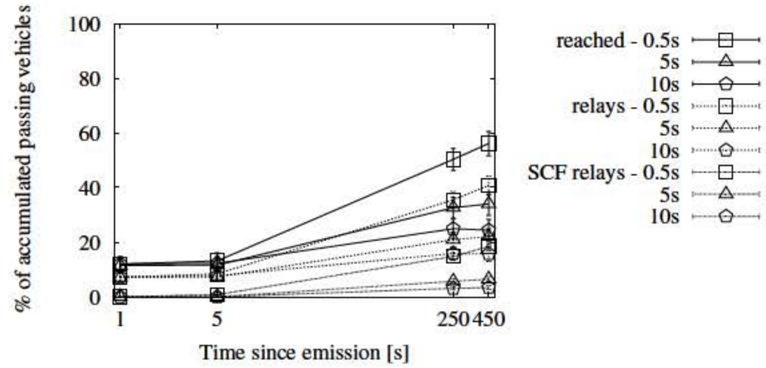
Figure 6.16: Sent messages with the fixed interval approach for store-carry-forward in the New York scenario.



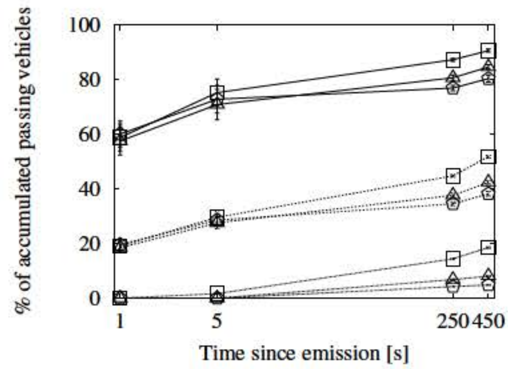
(a) Basic scheme - 25 veh/km^2

(b) Basic scheme - 100 veh/km^2

Figure 6.17: Forwarding ratio, or relation between sent messages and receivers with the fixed interval approach for store-carry-forward in the New York scenario.



(a) Basic scheme - 25 veh/km^2



(b) Basic scheme - 100 veh/km^2

Figure 6.18: Involved vehicles with the map polling approach for store-carry-forward in the New York scenario.

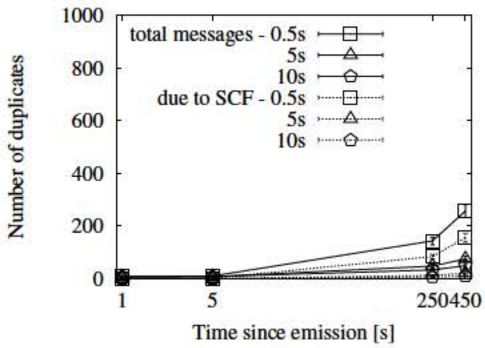
very clear to see in Figure 6.20, where the line for a 0.5 s period rapidly rises above one retransmission per receiver, while the other two remain below during the first 450 s.

Comprehensive Comparison

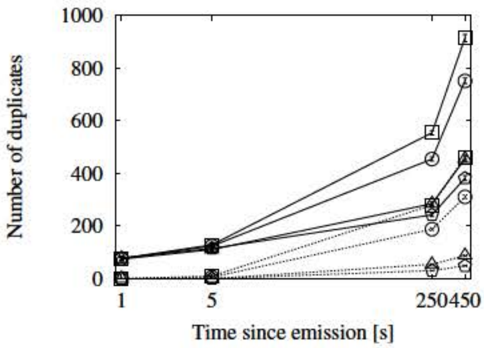
We focus especially on the graphs in figures 6.14, 6.17 and 6.20, so that we can compare the results from each approach easily. They offer a summary of the performance, as they relate the number of reached vehicles with the total number of duplicates.

First, we have confirmed that, the lower the density, the worse the overhead. Store-carry-forwarding is needed more often and hence the number of duplicates increases. However, we have seen that the number of receivers still does not reach the same value as in a higher traffic density.

The speed-adaptive strategy shows a good performance, keeping the ratio under one duplicate per receiver during the 450 s of the experiments. Map polling also offers very good results, as long as the interval is long enough. Checking the map every 5 s yields approximately the same outcome as the speed-adaptive approach. Doing the check every 10 s improves it slightly. The fixed interval strategy, configured with a

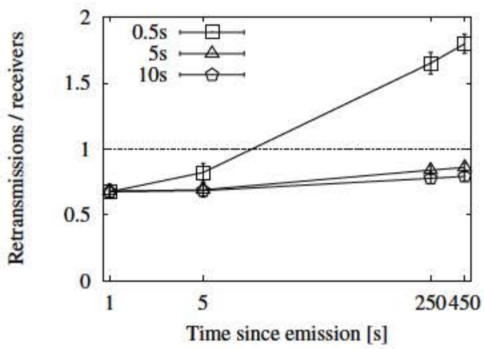


(a) Basic scheme - 25 veh/km^2

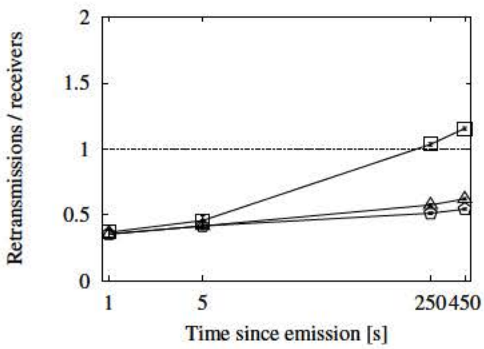


(b) Basic scheme - 100 veh/km^2

Figure 6.19: Sent duplicates with the map polling approach for store-carry-forward in the New York scenario.



(a) Basic scheme - 25 veh/km^2



(b) Basic scheme - 100 veh/km^2

Figure 6.20: Forwarding ratio, or relation between sent messages and receivers with the map polling approach for store-carry-forward in the New York scenario.

10 s retransmission period, also shows very similar results.

Regarding the other metrics, the fixed interval approach achieves a higher coverage at the cost of a large number of duplicates, as it about doubles the speed-adaptive overhead. The map polling option, on the other hand, caused a slightly lower number of messages than the speed-adaptive one, but its coverage was also slightly lower. So we choose the speed-adaptive strategy, as it is the approach that achieves the best compromise on the different metrics.

6.5 Performance Evaluation

We compare the basic scheme and the map-based urban scheme, together with the store-carry-forward mechanism for cities, with a well-known work from the state of the art, UV-CAST [Viriyasitavat et al., 2011], that we described in Section 2.2.3. In the evaluation by the authors, its parameter $\tau_{max} = 500\,\text{ms}$. We modify it to $\tau_{max} = 350\,\text{ms}$, to match our T_{max} value.

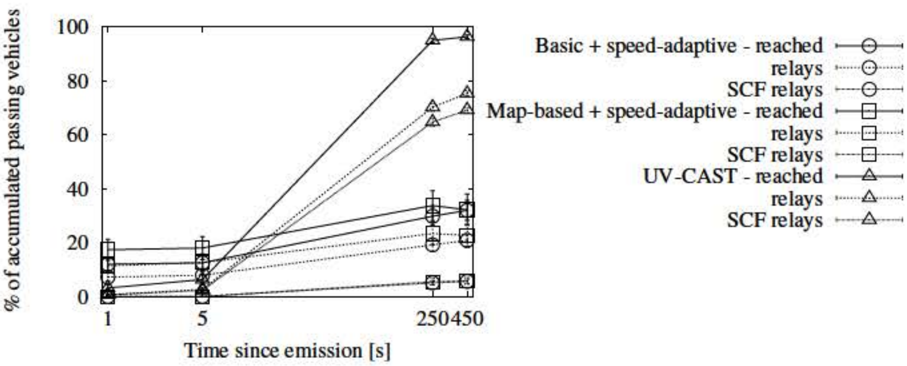
The graphs in Figure 6.23 show the performance results of our simulations. According to the graphs showing the involved vehicles (figures 6.21(a) and 6.21(b)), we can see that UV-CAST reaches a low number of vehicles in the first stage of the dissemination. However, it achieves an almost total coverage in the long run, even in low traffic densities. Our solutions, on the other hand, get to a higher number of vehicles in the first few seconds, especially in high densities, but the increase over time is limited. The cause of UV-CAST's high coverage is its overhead, as we can verify in figures 6.22(a) and 6.22(b). We can see that the vast majority of duplicates when using UV-CAST are due to its store-carry-forward mechanism. It is what lets the protocol reach such a high number of targets.

Finally, the ratio graphs in figures 6.23(a) and 6.23(b) summarize what we have just observed. Our alternatives' ratios grow together and slowly towards the one duplicate per receiver reference. UV-CAST, for its part, starts with a low ratio, what justifies the low coverage in the early dissemination stage, and rises fast to several duplicates per receiver. It is significant that it causes relatively more overhead as the density is higher, as opposed to our schemes.

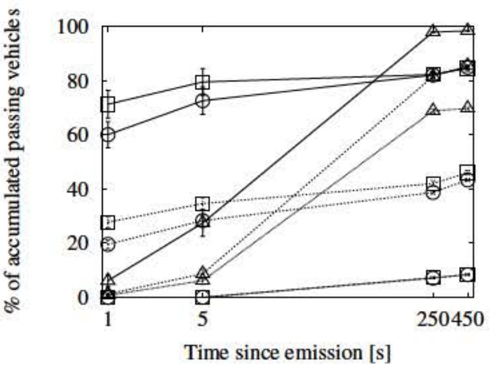
6.6 Conclusions

In this chapter, we have explored how to adapt the basic distance-based dissemination scheme to the special characteristics of the urban environment. Our first step was to test said scheme, without modifications, with a double goal: First, we got to tune its configuration parameter, T_{max}, to a fitting value in the new type of scenario. Second, we could check its performance for reference during the subsequent work.

The next task was to improve the basic scheme. Our intuition was to add some mechanism that would let vehicles detect when they are passing through an intersection and increase their chance to forward if so. This way, we would increase the chances of the message to be disseminated in other directions and reach more vehicles.

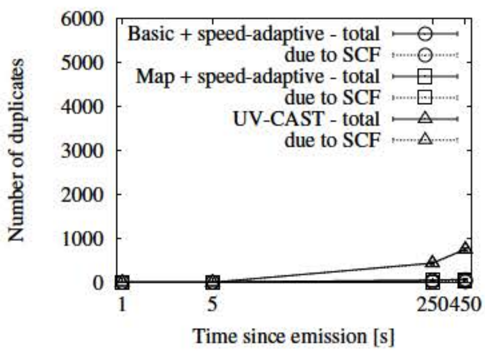


(a) 25 veh/km^2

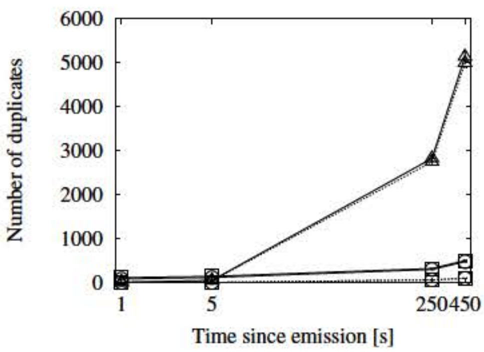


(b) 100 veh/km^2

Figure 6.21: Involved vehicles in comparison with UV-CAST in the New York scenario.

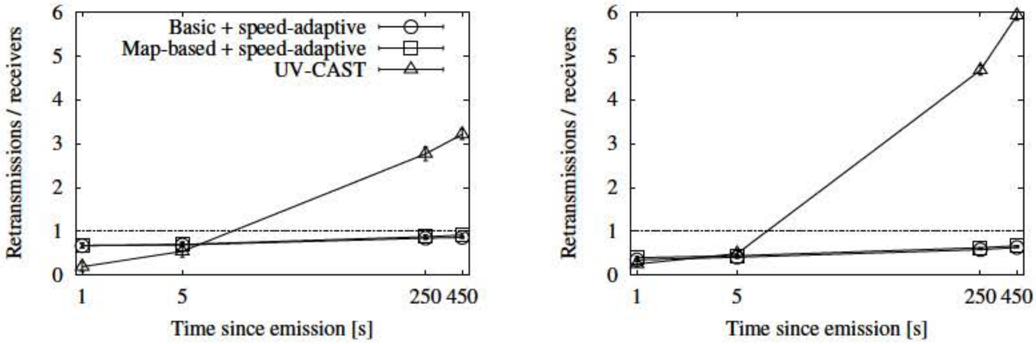


(a) 25 veh/km^2



(b) 100 veh/km^2

Figure 6.22: Sent duplicates in comparison with UV-CAST in the New York scenario.



(a) 25 veh/km^2 (b) 100 veh/km^2

Figure 6.23: Forwarding ratio, or relation between sent messages and receivers in comparison with UV-CAST in the New York scenario.

In order to do this, we compared two different approaches. One of them is checking the location coordinates in a digital map when a new message arrives. The other is finding out if the reception angle is more or less close to a straight angle or not. Vehicles that estimate that they are in an intersection, take part in a different time contention to gain precedence. We have tested them throughly via simulations. Our conclusions were varied. First, we got to find the most suitable values for the junction-specific maximum wait and the threshold angles. Also, we discovered that the angle-based approach detects intersections very well and incurs in a high overhead due to the intensive forwarding at corners. Finally, we learned that the adaptation to urban scenarios does not achieve a significantly better performance than the basic scheme. They do reach more vehicles but the number of necessary duplicates is also higher. We still had to try adding a store-carry-forward mechanism for cities, so that we could weigh the extra coverage achieved by the urban scheme.

We have created a custom store-carry-forward following the same principles that guided us for the roadway version: We use the reception of a new duplicate with a different TTL as an implicit acknowledgement of reception and taking over as relay. We base the delay before retransmitting for a second time or more, on a timer instead of an event. Finally, vehicles must skip forwarding if they are halted.

The timer for retransmissions could be set in different ways and we have considered three: with a fixed interval, based on the current vehicle's speed, and by polling the position of the vehicle in a digital map to check if it is at an intersection. The performance results we have obtained showed that the map-polling and the speed-adaptive approaches were good candidates, though the latter offered a better compromise on coverage and overhead. In addition, we observed that, no matter the initial coverage of the scheme, in the long run it gets to the same point in coverage and overhead, depending only on the approach for the retransmissions timer. When compared to UV-CAST, we see that we achieve a better coverage in the first stages with either of the two options, but UV-CAST gets an almost total coverage later, thanks to the high amount of duplicates its store-carry-forward mechanism issues.

So, our final conclusion is that we can apply two different schemes depending on the requirements of the application. If the source will repeat the message periodically, then using store-carry-forward does not make sense and the map-based urban adaptation should be applied. Otherwise, it is a good idea to use the basic scheme with the addition of the store-carry-forward for cities.

Chapter 7

Conclusions and Future Work

In this chapter, we present an overview of the main conclusions obtained from our work. Then, we outline the main contributions to the state of the art. Most of them have been published via articles in international conferences, a high-impact journal and the participation in national research projects. They are listed together with the results that appear in each of them in relation with this thesis. We end with some lines of further work that follow from the results detailed here.

7.1 Conclusions

In the realization of this dissertation, we have obtained valuable knowledge about the dissemination of information in VANETs and also other related aspects.

- We have learned about the standardization efforts by the American IEEE and the European ETSI, which have been intense during the last decade. The results are two sets of standards, DSRC and ITS respectively. They have been slowly released since 2009 and the first connected cars are appearing in Europe in 2015. Both standards sets are aware of each other and not completely incompatible, as they share almost the same PHY-MAC. On a higher level, and regarding multi-hop dissemination, they take very different approaches. In DSRC, multi-hop routes must be managed by IPv6. This cannot be done straight away, as IPv6 is not adapted to geographic routing yet, though there are researchers working on this. ITS, on the other hand, includes three multi-hop broadcast schemes in the definition of GeoNetworking, the multi-hop routing protocol. These have been provisional until recently, and are still subject of work.

- We have reviewed a varied selection of works from the literature on dissemination schemes for VANETs. Authors agree in three relevant metrics for evaluating a multi-hop broadcast scheme: coverage, redundancy and delay. Each solution focuses on improving the performance of one of the three depending on the final goal (reliability, efficiency or speed, respectively) at the cost of the other two. Reliability seems to be secondary to most applications, and most authors concentrate on speed or efficiency. A fast dissemination is interesting mainly for safety-related applications. An usual way of achieving it is by exchanging frequent status messages to create a backbone or cluster-based structure. Members of the backbone or cluster heads are preselected to forward a packet immediately in the event there is one. If reliability is not necessary, a fast algorithm like a probabilistic scheme or a binary decision are also applicable. Efficiency is important in most cases, especially if the application is delay-tolerant. The shared bandwidth is a limited resource and vehicular networks can get very crowded (for example, in downtown areas or traffic jams). Then, broadcast suppression techniques help in reducing the number of sent duplicates. A popular algorithm for this task is the distance-based scheme. It minimizes the number of hops that are necessary to cover a given area, and therefor the number of duplicates, too. Lastly, reliability can be achieved by implementing some kind of acknowledgement system, like handshakes or clustering. In line with this goal, some works also try to cover more nodes by applying a store-carry-forward mechanism that helps alleviating the effects of network partitioning.

- Counting on the current standards, and after reading numerous works from the state of the art, we have not found any solution that meets all our initial requirements: to prioritize efficiency, to be independent from infrastructure and from status updates, and to implement some mechanism that lets the message travel through disconnected regions. Still, we have identified some hints as the most popular dissemination strategy for efficiency, and the convenience to acknowledge receptions for overcoming network partitions.

- We have also learned that there are two very different types of scenarios—roadways and cities. We have reviewed their differences and the traffic models that have been proposed for each of them. The two main differences between these two types of scenarios are the topology and the consequent range of movements of vehicles in them. Their movements in roadways are restricted to a one-dimensional pattern, while urban areas allow bi-dimensional trajectories. Hence, routing and dissemination algorithms cannot be applied interchangeably. With regard to traffic models, we have presented some of the latest works on macroscopic modeling for the traffic of vehicles in roadways. They identify two regimes—dense and sparse traffic. Vehicles in dense traffic conditions usually form a connected network and the space between consecutive vehicles is approximately normally distributed. Sparse traffic leads to disconnected groups of vehicles, and their inter-space distribution is exponential. Inside cities, traffic modeling is much more complex than in roadways, because there are numerous options and factors that can affect vehicles movements. For this reason, the most common mobility models are microscopic. Specifically, the car following (CF) model is possibly the most widely used one and it is the base of many traffic simulators. We have offered a brief overview of three frameworks that implement mobility models based on CF: IMPORTANT, STRAW and SUMO. The last one has evolved and gained in popularity, and is now the mobility simulator in most current works. Thanks to all this information, we were able to design and test our solution in accordance with realistic conditions.

- We have seen how the research community has gone from general solutions, better suited and mainly tested on roadway scenarios, to specific schemes for cities. Urban scenarios pose the additional problems of vehicles frequently changing their direction and signal bouncing and blocking because of obstacles like buildings. Solutions for this type of topology focus on taking advantage of vehicles located at intersections. They usually implement relay selection mechanisms that promotes vehicles in intersections. For this task, some rely on digital maps and others use different metrics, like the neighbor density or the reception angles.

- One of the main needs was alleviating the problem of broadcast storms, that are prone to happen in traffic jams and in downtown areas, as we mentioned above. We have used the typical taxonomy of dissemination schemes in MANETs as our starting point to select one that could be the base of our solutions. We have chosen or created a scheme for each category: a simple probabilistic forwarding, a typical counter-based scheme, a distance-based implementation that is similar to others existing in the VANET literature, and an original traffic-based algorithm. We paid attention to three different metrics: the delivery ratio, the ratio of forwarders per receiver, and the average end-to-end delay to each reached vehicle. By simulating them in a simple roadway scenario, we have learned that the inability of the probabilistic scheme to adapt to different traffic densities yields poor results in terms of delivery ratio or redundancy, depending on the situation. Also, that the dissemination takes place in a very short lapse, in which the vehicles are almost static, so the relays should be selected based on their current connectivity (and not on expectations for the near future). The counter-based and the distance-based schemes showed good results because they are able to adapt to different traffic densities. Specifically, the distance-based one achieved the best performance in both the ratio of forwarders per receiver and the delivery ratio, making it our preferred option. In exchange, it is the slowest scheme of the set. We have created efficient dissemination schemes for roadways and urban scenarios by applying this distance-based contention. It uses a delay that is a function of the distance to the previous relay. This way, we also achieve independence from supporting infrastructure and from an updated knowledge base about the surrounding vehicles.

- We have followed different routes to suggest useful configuration values for the distance-based broadcast suppression scheme that we have chosen, depending on the complexity of the scenario model. As the roadway environment is assumed to be relatively simple, we could take the basic distance-based scheme as it was and optimize its redundancy via its configuration parameters. The first step was to work on its ratio of forwarders per receiver. We decided to do this via an analytical study, in which we also had to find the average distance from each relay to the next. We discovered that the scheme is already close to achieving the theoretical minimum. Its main drawback is the latency, due to the time-based contention at each hop. We were able to minimize it without compromising the coverage and the ratio of forwarders per receiver via a second analytical study. For the urban version, our intuition was to add some mechanism that would let vehicles detect when they are passing through an intersection and increase their chance to forward if so. This way, we would increase the chances of the message to be disseminated in other directions and reach more vehicles. In order to do this, we compared two different approaches. One of them is checking the location coordinates in a digital map when a new message arrives. The other is finding out if the reception angle is more or less close to a straight angle or not. Vehicles that estimate that they are in an intersection, take part in a different time contention to gain precedence. We have tested them throughly via simulations reached several conclusions. First, we discovered that the angle-based approach detects intersections very well and incurs in a high overhead due to the intensive forwarding at corners. Also, we learned that this type of approach does not achieve a significantly better performance than the basic scheme.

- We have found that, in sparse roadway traffic, and almost always inside cities, there are gaps or obstacles between groups of vehicles that stop the dissemination due to the lack of connectivity. In order to solve the eventual disconnections between groups of vehicles, we have designed a store-carry-forward mechanism that does not rely on information about the surrounding vehicles. The main problems that we had to solve were three: how to detect the necessity to activate the mechanism, when to schedule new retransmissions, and how to select the best relay for maximizing the success of the dissemination. We have had to create a different mechanism for each type of scenario. In roadways, the direction of the message and of the potential relays are unambiguous—respectively, away from the source and in their current direction. This has helped us be very specific about how to choose the relays and the best delay between successive retransmissions. On the other hand, urban scenarios are not so deterministic. The message needs to be disseminated omni-directionally and vehicles may turn at every intersection. Because of this, we have tried several algorithms that are "blind" to some degree and much less complex than the roadway counterpart. We have evaluated the performance of the complete solutions in contrast with the distance-based, broadcast suppression scheme alone. We have significantly risen the percentage of cases in which a message covers the whole ROI in cases of sparse or very sparse traffic. This has necessarily meant an increase in the number of emitted duplicates.

- As a collateral finding, we have checked the effect of different urban topologies on the dissemination. The results of our simulations with two real city maps (a regular layout from Manhattan, New York and a more complex arrangement from the Madrid city center) let us draw two conclusions. First, that the performance metrics may reach substantially different values in each scenario. Second, that leaving aside the absolute values of said metrics, the curve tendency and inflection points will be very alike. In summary, we can not say if a scheme is good or not on its own, but we can compare schemes and different configurations in one scenario, with confidence that the conclusions will be the same in other scenarios.

7.2 Summary of Contributions

According to the conclusions described above, we can sum up the main contributions that are fruit of the research carried out for this dissertation as follows.

- **Summary of the state of the art and standardization efforts in dissemination schemes for VANETs.** We have presented a selection of well-known solutions for the two types of VANET scenarios—roadways (or simple layouts) and cities. From among the vast literature on the subject, we have chosen a few representative schemes to illustrate the different goals that authors set for their solutions and the techniques they use to achieve them. This is preceded by an abstract on the American and European standards for VANETs, that have been developed in the last years, and an overview of dissemination schemes for MANETs that have also been applied to VANETs.

- **Design and optimization of a distance-based scheme for roadways scenarios, in accordance to the model for dense traffic.** We use a distance-based approach with the intention of meeting three of our requirements: low overhead, independence of infrastructure support and avoiding the use of a local base of neighbors information. Its application to the roadway environment is straight-forward and, thanks to the characteristics of this scenario, very successful. We have worked on optimizing its performance with an analytical study. An important step was taking into account the traffic model for dense roadways. Recent studies point out that the distribution of the distance between consecutive vehicles in such conditions is approximately normal. Most other works on dissemination schemes have chosen exponential or uniform distributions for their performance evaluation.

- **Creation of a store-carry-forward mechanism specific for sparse traffic situations in roadways.** In line with the rest of the scheme, we have designed a mechanism that maintains the independence from infrastructure support and from neighbors' status updates. We have created a set of rules for (a) triggering the activation of the mechanism, (b) choosing an appropriate delay before successive retransmissions, and (c) the selection of relays that optimize its performance. We have compared our complete scheme with a well-known solution, DV-CAST, in a series of different density situations. The results show that our scheme meets our requirements satisfactorily.

- **Set of dissemination schemes for cities.** We propose three different algorithms for reducing the high overhead that urban environments suffer from. One of them is the same scheme that we have created for roadways (minus the store-carry-forward part). The other two are intended for detecting and increasing the chance of retransmission from intersections. Each of them offers advantages in different aspects of the performance. Forwarding at intersections favors the successful dissemination and increases the delivery ratio, but it deteriorates the overhead. We decide on the map-based algorithm because it offers the best compromise on the two aspects.

- **Store-carry-forward mechanism for overcoming disconnections urban environments.** In this type of scenario, vehicles travel in any direction and may change it at every intersection. Due to this, we cannot apply a set of rules as specific as those we use in roadways. We opt to adopt as much as we can from there, and configure a retransmission mechanism that is not as aware of directions of the message and vehicles. Among several techniques, we select one that schedules retransmissions in function of the current speed of the carrier vehicle. We have also observed that, regardlessly of the initial delivery ratio of the scheme, the store-carry-forward mechanism is what determines the coverage in the long run. We have compared the complete scheme with UV-CAST: the latter starts with a lower delivery ratio, and achieves an almost total coverage later, higher than our solution, thanks to the high amount of duplicates its store-carry-forward mechanism issues.

- **Different proofs of concept of the scheme for roadways as part of non-safety applications.** We have had the opportunity to develop three proofs of concept to prove the usefulness of the scheme. One of them was fruit of a joint work with researchers from the Universitat Politècnica de Catalunya (UPC), in which the scheme is route environmental information towards collection points. Another use case is as the basis of a traffic information system, developed during a research stay in the Technische Universitaet Muenchen (TUM). A third application in which we have used it is an advertising system for gas stations.

7.3 Impact of the Research

With respect to publication and dissemination, the content of this thesis was mainly developed as a research line in a national R&D project, CONSEQUENCE[1]. Most of our findings about disconnection-resilient dissemination schemes are the result of the work package about "Continuity of Service". This project left open lines for further work, that are being currently tackled by the new national R&D project, INRISCO[2]. In this one there is a specific work package devoted to "Dissemination of Information Over Infrastructure-less Networks."

[1] `http://consequence.it.uc3m.es`

[2] `http://inrisco.org`

In addition, we also disseminated our results through the publication of scientific articles. The papers that contain this thesis' contributions are detailed below. For each one, we indicate the kind and date of publication and its contents.

7.3.1 High Impact Publications:

1. Title: *A Bandwidth-Efficient Service for Local Information Dissemination in Sparse to Dense Roadways.*
   Authors: E. Garcia-Lozano, C. Campo, C. Garcia-Rubio, A. Cortes-Martin, A. Rodriguez-Carrion, P. Noriega-Vivas.
   Journal: Sensors. ISSN 1424-8220. Printed version in Vol. 13, Iss. 7, pp. 8612 - 8639, July 2013. (Impact Factor 2013: 2.048) [Garcia-Lozano et al., 2013a].

   In this article, we expand the work presented in [Garcia-Lozano et al., 2012b] by explaining the design of a custom store-carry-forward mechanism for roadways. We assess the performance of the addition through extensive simulations, including different channel loads and in comparison to a well-known solution.

2. Title: *A new traffic information service for smart consumer devices.*
   Authors: E. Garcia-Lozano, W. Woerndl, C. Campo.
   Conference: 2014 IEEE International Conference on Consumer Electronics (ICCE). Co-located with the International CES in Las Vegas, USA, January 2014. [Garcia-Lozano et al., 2014b].

   This article is fruit of my research stay with the group of Applied Informatics and Cooperative Systems in the Technische Universitaet Muenchen in Germany. This proof of concept shows how our dissemination scheme for roadways, complete with the custom store-carry-forward mechanism, can serve as the base of a traffic information system.

3. Title: *Bandwidth efficient broadcasting in VANETs.*
   Authors: E. Garcia-Lozano, C. Campo, C. Garcia-Rubio, A. Cortes-Martin.
   Conference: 8th IEEE International Wireless Communications and Mobile Computing Conference (IWCMC 2012). Limassol, Cyprus, August 2012. (CORE Rank: B) [Garcia-Lozano et al., 2012a].

   Here, we present the initial evaluation of different dissemination schemes that have been adapted to vehicular networks from the state of the art in MANETs. This work led us to the conclusion that a distance-based algorithm was what best fitted our requirements in regard to low redundancy over high dissemination speed.

7.3.2 Other Publications:

1. Title: *An efficient, eco-friendly approach for push-advertising of services in VANETs.*
   Authors: E. Garcia-Lozano, C. Campo, C. Garcia-Rubio, A. Cortés-Martín, A. Rodriguez-Carrion, P. Noriega-Vivas.
   Conference: 6th International Conference on Ubiquitous Computing and Ambient Intelligence (UCAmI 2012). Vitoria, Spain, December 2012. [Garcia-Lozano et al., 2012b].

   This work explains the adaptation of the scheme for roadways, in the framework of a proof of concept. Regarding the scheme alone, we analyze its forwarding ratio and average per-hop delay. The proof of concept consists on an advertising service for gas stations.

2. Title: *A distributed, bandwidth-efficient accident prevention system for interurban VANETs.*
   Authors: E. Garcia-Lozano, C. Tripp Barba, M. Aguilar Igartua, C. Campo.
   Conference: 4th International Conference on Smart Communications in Network Technologies (SaCoNeT 2013). Paris, France, June 2013. [Garcia-Lozano et al., 2013b].

   This work is a result of the collaboration with researchers from the Universitat Politècnica de Catalunya in the framework of a national project. In this other proof of concept, we integrate the same scheme as part of a solution for accident prevention. We propose its use for the transport of non-urgent data between vehicles that collect vehicular traffic data and central processing units.

3. Title: *Bandwidth-efficient techniques for information dissemination in urban vehicular networks.*
   Authors: E. Garcia-Lozano, C. Campo, C. Garcia-Rubio, A. Cortes-Martin.
   Conference: 11th ACM symposium on Performance evaluation of wireless ad hoc, sensor, & ubiquitous networks (PE-WASUN 2014). Montreal, Canada, September 2014. [Garcia-Lozano et al., 2014a].

   This article contains the first results from our work adapting the distance-based dissemination scheme to urban environments. We consider three different implementations, based on different ways of recognizing junctions and reacting to them. We tested the schemes in different real city maps, that let us assess their general performance.

4. Title: *Adapting a Bandwidth-Ecient Information Dissemination Scheme for Urban VANETs.*
   Authors: E. Garcia-Lozano, C. Campo, C. Garcia-Rubio, A. Rodriguez-Carrion.

Conference: 9th International Conference on Ubiquitous Computing and Ambient Intelligence (UCAmI 2015). Puerto Varas, Chile, December 2015. [Garcia-Lozano et al., 2015].

This last publication contains a more thorough examination of the different configuration parameters that play a role in the three adaptations of the scheme to cities. In addition to optimizing the performance, we reached a better understanding of the strengths and weaknesses of each one.

7.4 Lines of Future Work

We consider that we have met our goals to a high degree and obtained satisfactory results. However, if given the opportunity and the necessary resources, we consider very interesting the following lines of further work.

First, we would like to further investigate the urban scenario. Given its complexity, there are multiple approaches that could be considered.

- We have considered two different alternatives to help spread messages by additionally forwarding at intersections. These techniques helped reach more vehicles in the ROI during the first seconds since the emission of the message, at the cost of an increased redundancy. There are multiple other approaches that could be adopted in an attempt to reduce the number of issued duplicates. For example, selecting as relays vehicles at intersections exclusively, as proposed in [Sanguesa et al., 2015]. An intermediate solution would be to promote vehicles at intersections as relays, and using the furthest from the sender if there is not any in such a location. A possible way to implement this could be by allocating different time slots for each contention—first for vehicles at intersections and then, if there is not any new relay yet, for the rest.

- Regarding the techniques for the recognition of intersections, we have studied two alternatives but there are other possibilities that could be interesting to try. For example, if we assume that the penetration of the technology is full and vehicles are frequently emitting beacons, the relative directions of reception could also indicate if the vehicle is near an intersection. Additionally, not receiving any of them would indicate that the vehicle is isolated and it could activate store-carry-forwarding without having to retransmit and wait for a new duplicate.

- Several authors consider that store-carry-forwarding in such a scenario is inefficient and that a source should emit its message periodically instead. So, an interesting line of work would be to study if periodic emissions are indeed preferable over store-carry-forwarding and, if so, in which conditions.

- Finally, it would be interesting to study the performance of the urban scheme under different channel load conditions, like we did with the roadway solution.

We have also had the opportunity to develop several proofs of concept for the latter. We would like to present applications based on the urban solution, too. For example, an advertising system for shows, similar to the gas station announcement service.

Another line of future work is about creating a holistic solution that a vehicle can execute regardlessly of its location. We have created an scheme for roadways and a set of schemes for cities. We envision an algorithm that integrates them into an only protocol that applies each scheme depending on the detected type of scenario. In order to do this, it is necessary to take a series of steps.

- First, we need to study connecting areas, like spaghetti junctions and city outskirts, that do not correspond well with any of the two scenario types. We need to understand the vehicles mobility and dissemination challenges that are present in them, and perhaps how they are related to the studied scenarios.

- Next, we need to identify the key metrics values that determine the change of scenario. These metrics may be the traffic density, the vehicle's speed or others. Depending on the metric, vehicles may have direct access to its value (the current speed, for example) or they will have to infer it (as would be the case for the traffic density). In the latter case, we would have to provide mechanisms for the vehicles to acquire the data they need.

- The last step will be to integrate the sensing mechanism, the decision algorithm and the dissemination schemes into an only protocol.

Lastly, it would be very interesting to evaluate the solutions with real traffic traces. There are datasets like the TAPAS Cologne project[3] that could be useful for this task. This would let us know, first, if the simulation environment is truly realistic, and second, if the performance of our schemes is acceptable for real traffic patterns. In the specific case of the TAPAS Cologne traces, they contain a large area including an urban center and radial roadways. This would make it a wonderful tool for testing the holistic solution that we have just explained.

[3] http://sumo-sim.org/userdoc/Data/Scenarios/TAPASCologne.html

Acronyms

AODV Ad hoc On-Demand Distance Vector Routing.

BTP Basic Transport Protocol.

C-ITS Collaborative Intelligent Transport Systems.

CAM Cooperative Awareness Message.

CBF Contention-based forwarding.

CBRP Cluster Based Routing Protocol.

CEN Comité Européen de Normalisation.

CSMA/CA Carrier Sense Multiple Access with Aollision Avoidance.

DENM Decentralized Environmental Notification Message.

DIFS DCF (Distributed Coordination Function) Interframe Space.

DSR Dynamic Source Routing.

DSRC Dedicated Short-Range Communications.

ETSI European Telecommunications Standards Institute.

G5 ITS standard for the access layer, based on 802.11p, that works in the 5GHz band.

GF Greedy Forwarding algorithm.

GN6 Transmission of IPv6 Packets over GeoNetworking Protocols.

GPS Global Positioning System.

i.i.d. independent and identically distributed.

IEEE Institute of Electrical and Electronics Engineers.

IPv6 Internet Protocol version 6.

ISO International Organization for Standardization.

ITS Intelligent Transportation Systems.

ITS-S ITS sub-system.

LLC Term for the logical link control layer. It is the upper sublayer of the data link layer (layer 2) of the seven-layer OSI model of computer networking.

MAC Term for the medium access control or media access control layer. It is the lower sublayer of the data link layer (layer 2) of the seven-layer OSI model of computer networking.

MANET Mobile Ad Hoc Network.

MFR Most Forward within Radius.

MIB Management Information Base.

OLSR Optimized Link State Routing Protocol.

PBSM Parameterless Broadcast in Static to Highly Mobile ad hoc network protocol.

PHY Term for the implementation of the physical layer or layer 1 in the seven-layer OSI model of computer networking.

RFID Radio Frequency IDentification.

RSU fixed infrastructure with communication capabilities in a vehicular networking scenario.

SCTP Stream Control Transmission Protocol.

SIB Security Information Base.

TCP Transmission Control Protocol.

TCP/IP It is the computer networking model and set of communications protocols used on the Internet and similar computer networks.

TTL Time To Live.

UDP User Datagram Protocol.

V2I Vehicle to Infrastructure.

V2V Vehicle to Vehicle.

VANET Vehicular Ad Hoc Network.

WAVE Wireless Access in Vehicular Environments.

WSM WAVE Short Message.

WSMP WAVE Short Message Protocol.

Symbols

α_{max} maximum threshold for the angle that forms the current vehicle's trajectory and its line of sight to another vehicle, to assume that they are different streets.

α_{min} minimum threshold for the angle that forms the current vehicle's trajectory and its line of sight to another vehicle, to assume that they are different streets.

$\Delta\alpha$ difference between α_{max} and α_{min}.

d_{center} distance to the junction center.

$\Delta\, t_{max}$ sum of W, T_{max} and the maximum time it takes the network to process the packet (collision resolution and propagation).

d_j generic threshold distance to determine if another vehicle is located at the same intersection.

d_{min} distance to the closest device from which this vehicle heard a duplicate of the same packet almost simultaneously.

r reception range, or coverage radius of a vehicle's or RSU's antenna.

ρ traffic density in veh./km.

$r_{junction}$ the radius of a given intersection.

R_{target} radius of the area of interest (ROI) for the dissemination.

τ minimum difference between the delays calculated by two consecutive nodes, so that the second hears the first's transmission before attempting to forward.

T_j maximum wait for vehicles in junctions.

t_j junction-specific time contention.

T_{max} maximum value for the forwarding delay t_w.

t_w delay a vehicle has to wait before forwarding a message in order to prioritize the vehicle most apart from the last relay.

v_{max} maximum legal speed in the roadway.

W short time during which a vehicle waits for almost simultaneous duplicates before computing a forwarding delay t_w.

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